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Detailed Thermal Performance Measurements and Cost Effectiveness of Earth-Sheltered Construction: A Case Study

J. E. Christian

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Energy Division

DETAILED THERMAL PERFORMANCE MEASUREMENTS AND COST EFFECTIVENESS OF EARTH-SHELTERED CONSTRUCTION: A CASE STUDY

J. E. Christian

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NOMENCLATURE

A_F	heated floor area
CCE	cost of conserved energy
COP	heat pump coefficient of performance
d	annual discount rate
E	annual energy savings (kWh/year)
G	sum of all heat gains to the building
H_c	deviation from the standard internal gain value
H_m	measured heat input from heating system (W/h)
I	incremental investment ($)
I_a	floor and weighted standard internal gain
I_s	actual measured internal gain in watts per unit of floor area from people, appliances, and lighting
L	sum of all heat losses to the building
n	lifeline of investment (years)
Q	heat flux
R	residual error in building energy balance
RSI	metric conversion for R-value
R-value	thermal resistance of wall component, the reciprocal of thermal conductance $\{(m^2 \cdot {}^\circ C)/W\ [(ft^2 \cdot {}^\circ F \cdot h)/Btu]\}$
T_i	average measured inside air temperature
U	heat conduction $\{W/(m^2 \cdot {}^\circ C)\ [Btu/(h \cdot ft^2 \cdot {}^\circ F)]\}$
UA_w	overall thermal conductance $\{W/{}^\circ C\ [Btu/(h \cdot {}^\circ F)]\}$
ΔI	internal load correction term used for normalization
Δt	deviation from the standard indoor average temperature

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ABSTRACT

Earth-covering, solar gain, and massive construction are the design concepts successfully blended to produce an energy-efficient, durable, and comfortable building. Twenty-four-hour-quiet sleeping quarters and quality office space were the first design objectives of this building; these were successfully accomplished. The data acquisition system and a unique energy-balance analysis documents the thermal performance of each envelope component. Since the building's typical number of occupants, size, and internal electric loads are similar to those of a large residential building, the energy-performance data are extended to the residential marketplace. First-cost estimates for the whole building, earth-covered roof, and bermed wall are used along with the detailed measured energy-use data to estimate cost effectiveness using residential economics criteria, such as 3% discount rate and 30-year life. The results from this analysis confirm the fact that earth, sun, and mass can save substantial amounts of annual and peak energy demand. However, further construction cost reductions are needed to produce more favorable cost effectiveness in the residential market arena.

The overall thermal conductance value of this building is lower than the average values from the 300 low-energy residences as reported in the Building Energy-Use Compilation and Analysis, Part A (BECA-A), data base. However, the balance point of this building, with mechanical ventilation to ensure about 0.5 air change per hour, is substantially higher than those reported for low-energy residential buildings. This suggests that most of the energy-efficient homes either have an air-to-air heat exchanger or infiltration levels far below the generally accepted 0.5 air change per hour to ensure healthy indoor air quality.

Reflective insulating blinds were installed in this building and have enhanced the daylighting and usability of the building. However, the small thermal benefit of increased window nighttime R-value (60%) is offset by raising the shading coefficient of the windows and increasing the heat loss through the roof by about 25%.

1. INTRODUCTION

Earth covering, solar gain, and massive construction team up to provide an energy-efficient, durable, and comfortable building. However, the question of whether these energy-saving features are cost effective still remains. The Joint Institute Dormitory,[1,2] a 372-m^2 (4000 gross ft^2) office-dormitory equipped with 100 sensors and a data acquisition system designed to store hourly thermal performance data from February 1982 to October 1984, provides a penetrating look at a number of energy-saving construction techniques. One of the objectives for collecting these data is to determine cost effectiveness based on field thermal performance of the whole building, including an earth-covered roof, bermed north wall, insulated concrete slab floor, structural thermal mass coupled with direct solar gain, and reflective insulating blinds. The locations of these components within the building are shown in Fig. 1 along with the floor plan and building cross section.

Confidence in the data base derives from the following: weekly energy balances using heat gain and loss measurements closing on average to within 10%, annual load measurement agreements with predictions from DOE-2.1B (ref. 3) simulation runs using 1982 local weather, tracer gas studies of building air exchange, and infrared surveys and duplicate envelope heat flux component measurement techniques. Two reports have been written on the analyzed building data.[1,2] One covers the heating season and a second, the cooling season. This report uses the detailed measurements as the bases for estimating annual energy savings with respect to more conventional energy-conscious wood-frame residences. The energy savings along with incremental cost estimates are used to determine cost effectiveness.

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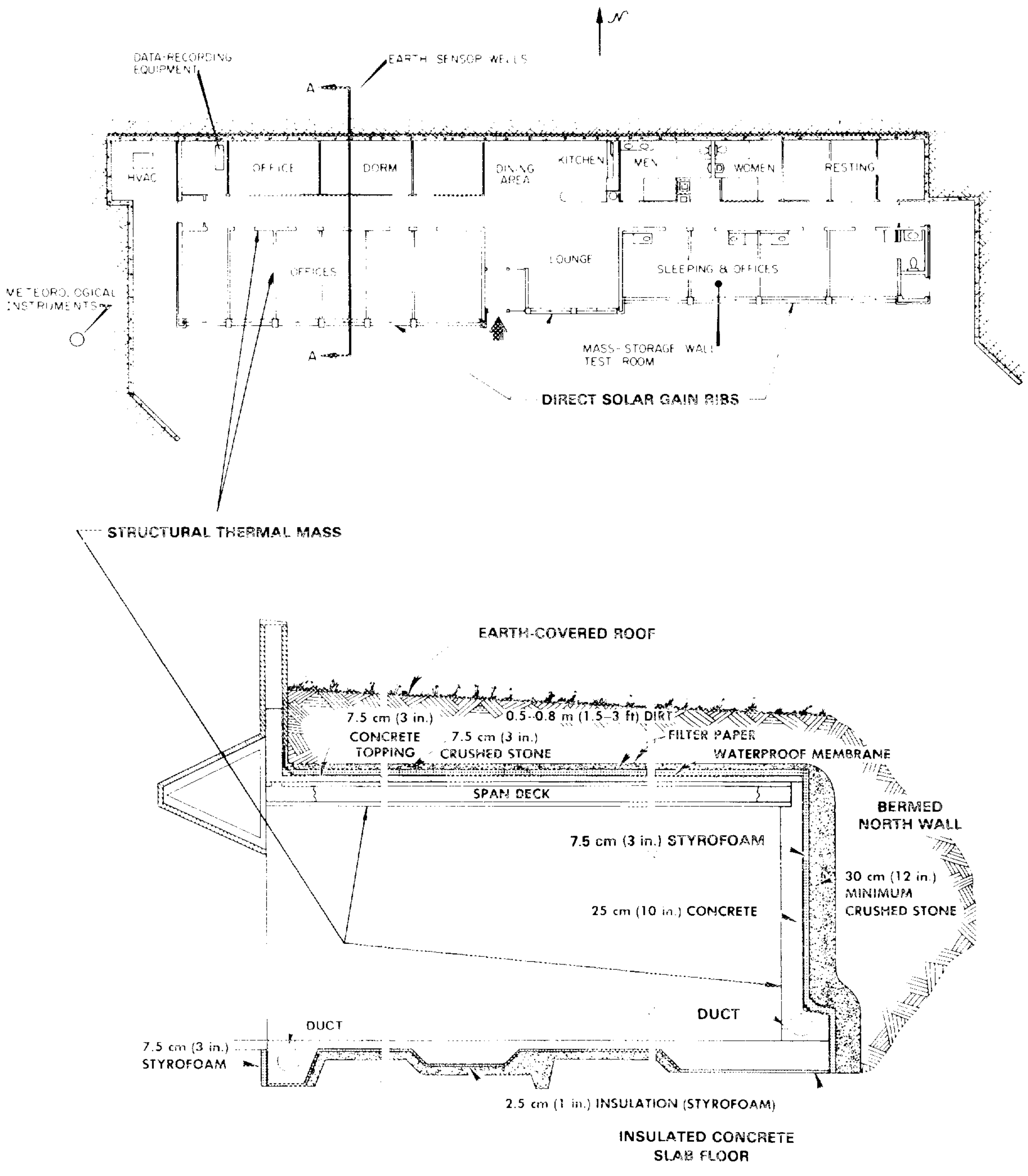

Fig. 1. Floor plan and north-south cross section.

2. BUILDING DESCRIPTION

2.1 ARCHITECTURAL FEATURES

Two major energy-saving design concepts realized in this building are earth tempering and passive solar gain. The building contains 345 m^2 (3700 ft^2) of heated floor space used for offices, dormitory rooms, and a lounge and dining area. Figure 2 shows the Joint Institute Dormitory south facade and the north face as seen from the road approaching the main entrance to Oak Ridge National Laboratory (ORNL), located in east Tennessee. The north

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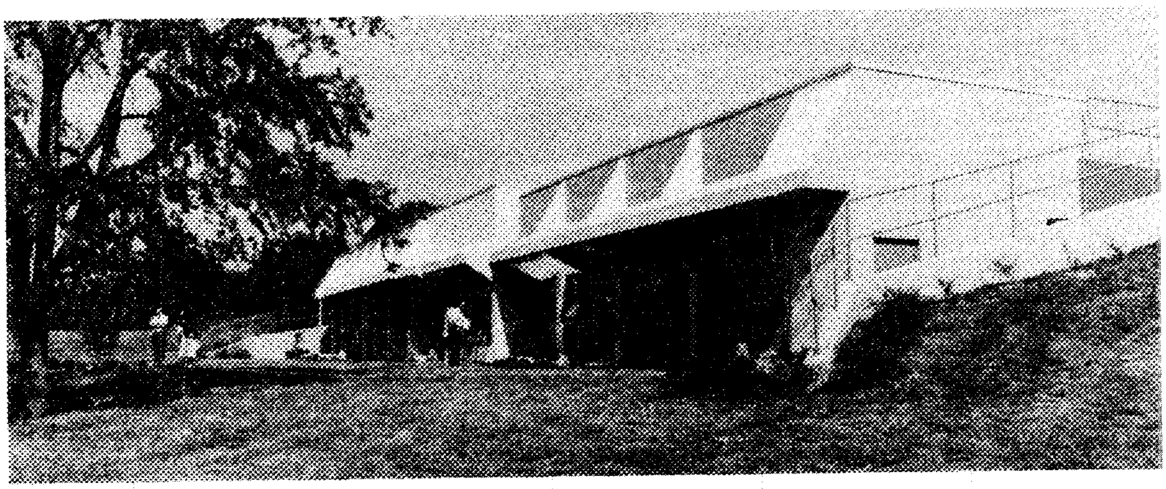

(a)

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(b)

Fig. 2. Joint Institute Office and Dormitory: *(a)* south facade, and *(b)* north face.

wall and part of the east wall and roof are covered with earth and planted with grass and small shrubs. The earth provides a number of desirable features: a visual screen of other buildings from the highway [less than 11 m (35 ft) away from the dormitory rooms] that leads to the main entrance of ORNL, a sound barrier completely blocking the noise from automobiles and trucks traveling at highway speeds, a thermal mass that provides a heat sink during the early summer months, shelter from direct solar insolation, and smaller temperature differences across the envelope components. Parts of the south, west, and east walls are block construction, externally insulated with 7.5 cm (3 in.) of expanded polystyrene with an epoxy-covered coating.

The south-facing glass area amounts to 17% of the net floor area. The windows were retrofit with reflective insulating blinds in November 1983. Therefore, thermal performance data are available before and after the window management system was added. Reflective insulated blinds provide direct solar gain to the masonry ceiling, enhancing daylighting and absorption of heat for release at night when the space cools and auxiliary heating would ordinarily be needed.

The building envelope construction, primarily poured concrete and masonry, is shown by the building cross section in Fig. 1. The north wall is insulated with extruded polystyrene and faced with sloping earth, and the exposed walls are externally insulated with expanded polystyrene and covered with an epoxy system that looks like stucco. The roof consists of precast concrete sections covered by 5 to 7 cm (2 to 3 in.) of poured concrete to provide a smooth adhesive surface for a waterproof membrane. The membrane is covered by 7.5 cm (3 in.) of extruded polystyrene insulation, a full 7.5-cm (3-in.) French drain in the form of a gravel seam, filter paper, and earth sloping from 0.76 to 0.46 m (2.5 to 1.5 ft).

2.2 MECHANICAL EQUIPMENT

The heat pump circulating fan operates continuously, preventing air stagnation, aiding thermal mixing, and introducing a steady-state level of background noise. Supply air ducts are located within the wall footings to enhance the coupling between the building air and effective thermal mass in the envelope. Most of the exhaust air is vented through two exhaust fan ports in the roof, one in the restrooms and a second in the kitchen. The exhaust fan in the restrooms is controlled by a light switch in each restroom. The kitchen fan is controlled by a switch in the equipment room and generally is not activated. Repetitive air exchange measurements using tracer gas techniques indicate that the air change rate varies from 0.4 air change per hour with no exhaust fan operation to 0.7 air change per hour with one fan and 1.2 air changes per hour with both exhaust fans operating. The exhaust fan operation is checked every minute, and the operating time is recorded hourly.

The three entrances to this building are through vestibules. Results from the tracer gas air change rate tests show no significant differences in air change rate as a function of door openings. The vestibule doors are closed at all times so the variable traffic rate into and out of the building does not alter the fact that air exchange in the building is predominantly a function of ventilating fan operation.

Space heating and cooling in this building are provided by a heat pump with a manufacturer's nominally rated 12.3-kW (3.5-ton at 95°F) heat pump and enthalpy-controlled economizer. The measured output of the installed heat pump unit was about 20%

below rated capacity; however, this was apparently caused by installation problems and was not the fault of the mechanical package. The measured heat pump performance is less than the manufacturer's rating because of a number of factors, the major one being low circulating air flow caused by constrictions in the supply duct located in the concrete footing.[2] The economizer control is set to bring in ambient cooling only when the outside air enthalpy is below the inside air enthalpy. Because the building circulating fan runs continuously, during those times when the outside air enthalpy is less than the inside air enthalpy, the economizer cycle essentially increases the air change rate to about four per hour, providing additional cooling with no additional electric energy expenditure.

2.3 BUILDING OPERATION

The single thermostat located in the north zone of the building was manually set to maximize thermal comfort by using a thermal comfort meter and recording the predicted mean vote (PMV) in various positions within the building. The PMV scale is an index that predicts the mean value of the subjective ratings of a large group of people on a seven-point thermal sensation scale ranging from −3 (cold) to +3 (hot). The subjective and physiological reaction of a person to the thermal environment is determined by the rates of a person's heat generation and heat emission, which in turn are functions of six parameters: air temperature, mean radiant temperature, air velocity, humidity, the individual's metabolic rate, and the thermal insulation of clothing. When any combination of these factors satisfies the comfort equation derived by Professor P. O. Fanger, most people will feel thermally comfortable.[4] People who are thermally neutral do not know whether they would like to be warmer or cooler. The thermostat was set to keep the entire building within a PMV range of 0 to +0.5 during the cooling season and −1.0 to +0.5 during the heating season. The north zones surrounded on three sides with earth contact were typically much more stable and had a much smaller PMV diurnal cycle amplitude. The south-facing windows dominated the envelope heat flows both in the heating and cooling season. The south-facing offices with the full glass exposure exhibited the greatest diurnal fluctuation. This part of the building required most of the space conditioning.

3. WHOLE-BUILDING ANALYSIS

3.1 METHODOLOGY

The true cost effectiveness of a well-built, inspiring building cannot be estimated. Twenty-four-hour-quiet sleeping quarters and quality office space availability were the first design objectives of this building; these were successfully accomplished. The cost-effectiveness estimate for the whole building is based on the cost difference between an earth-covered, passive solar, and massive construction type building and an energy-efficient above-grade building of the same floor space. The savings resulting from the incremented cost is assumed to come from energy savings only. No additional cost savings is estimated for longer life, enhanced acoustical properties, tornado protection, bomb-shelter potential, aesthetic improvements, and lower insurance rates. These costs may or may not be significant and should be a factor on a case-by-case basis to suit an individual's decision criteria. The focus of this research is on thermal performance. Therefore, the approach used in this report consists of first determining the energy usage and second normalizing the energy usage to derive performance indicators (such as overall thermal conductance of the building) and energy savings of this building compared with conventional construction and alternative low-energy buildings. Finally, an estimate of cost effectiveness is made using national average energy costs.

3.2 ENERGY USE

3.2.1 Whole Building

Figure 3 shows monthly kilowatthour usage for a 3-year period. The monthly kilowatthour data categorizes the four seasons by showing a distinct rise in total energy usage in the winter and in the summer. The fall months show consistently low energy use, and the spring months appear to reflect the erratic annual weather patterns in east Tennessee.

This office-dormitory uses energy at a total annual rate of 81.7 kWh/m^2 (25,900 Btu/ft^2). Assuming a rate of \$0.07/kWh, the total energy bill to run this building is about \$2128 per year or \$177 per month. The maximum monthly cost, about \$300, tends to occur in January. The minimum monthly energy cost, \$120, tends to occur in October when little space conditioning is needed. From this information, it would appear that on the average \$58 per month goes toward providing heating or cooling from the heat pump. This building has submetered data for lights, water, heating, receptacles, and kitchen appliances. From the additional data, greater insight can be gained into how energy is being consumed. A typical annual percentage division of electricity usage in this building is shown in Fig. 4. The heat pump and lights account for almost 70% of the total annual usage.

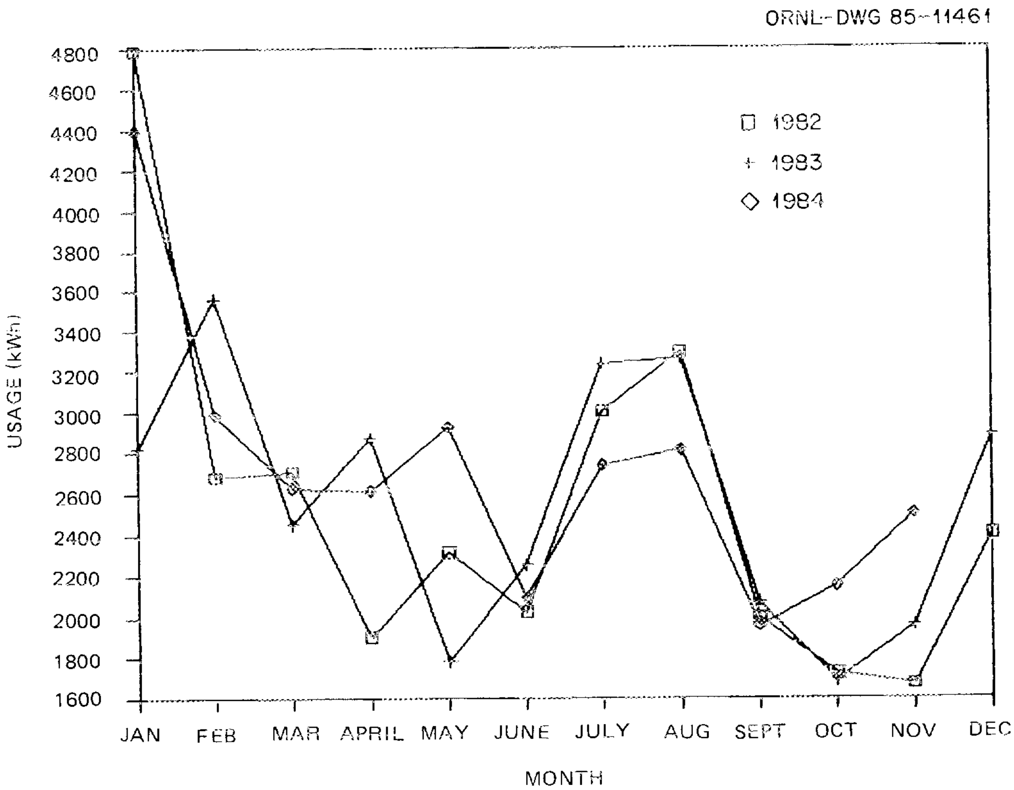

Fig. 3. Total monthly kilowatthour usage for 1982, 1983, and 1984.

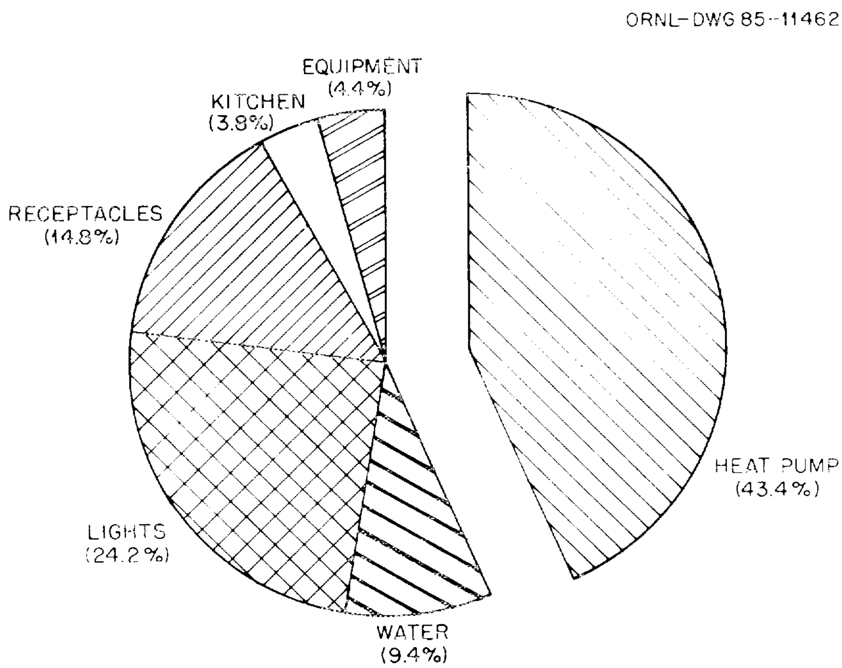

Fig. 4. Percentage breakdown of electricity usage for 1983.

3.2.2 Heat Pump

The heat pump and circulating fan are on the same meter, and the circulating fan in this building runs continuously. Figure 5 shows the monthly heat pump and fan energy consumption. The general pattern seen in Fig. 3 for total energy usage is repeated for the heat pump monthly energy consumption. One conclusion drawn from Figs. 3 and 5 is that the internal electric use is relatively constant from month to month. Figure 5 shows that January, July, and August represent almost half of the heat pump usage for the entire year. The large heating need in this building in January is due primarily to the predominance of cold cloudy days and the resulting low solar saving fraction for this month in 1982, 1983, and 1984.

In July and August, the major need for cooling comes from sensible heat gain through the south-facing windows and the latent heat caused by the necessary 0.5 to 0.7 air change per hour for ventilation.

The heat pump and continuous circulating fan use about 13,500 kWh per year: 8100 kWh during the heating season and 5400 kWh during the cooling season. Subtracting the energy consumption of the circulating fan gives the energy used to run the compressor and resistance heaters. This energy usage is 6000 kWh during the heating season and 3915 kWh during the cooling season. The annual energy cost for running the heat pump, including the fan, averages about $945. The largest single monthly heating bill, assuming a national average electric cost of $0.07/kWh, is around $196. Slightly less than half of the building's total energy use results from space conditioning needs.

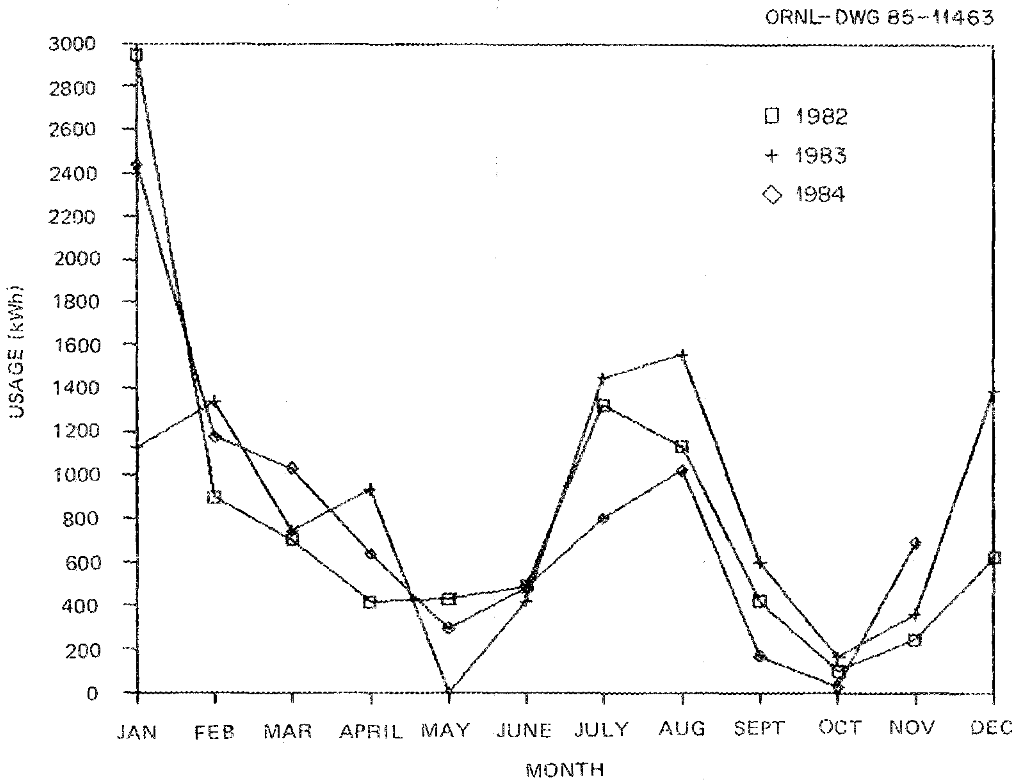

Fig. 5. Heat pump monthly kilowatthour usage for 1982, 1983, and 1984.

3.2.3 Lights

The monthly lighting energy does not vary seasonally, as shown by Fig. 6. One might expect to see more lights on in the winter season, when daylight is shorter. In this building, the natural lighting is adequate for more working hours in the winter than in the summer when the sun is higher and the extended overhang shades almost all of the direct sunlight. The annual electric lighting use totals 18 kWh/m^2 (1.7 kWh/ft^2) of floor area. Largely because of the lack of natural light penetrating the north zones of this building, some lights are left on all the time. About 25% of lighting energy usage is for outside lighting.

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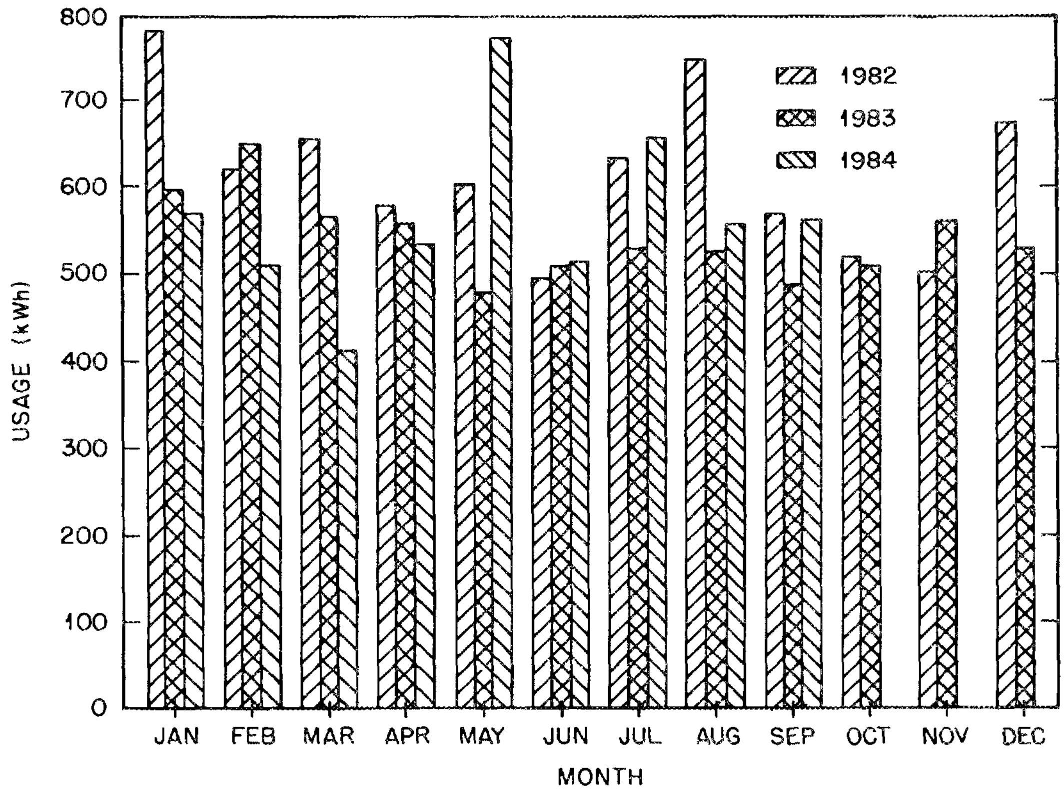

Fig. 6. Lights monthly kilowatthour usage for 1982, 1983, and 1984.

3.2.4 Water Heating

The water heating usage shown in Fig. 7 fluctuates slightly more than that for lights but still is quite stable throughout the year. The average annual water heating electric use totals 6940 kWh per year. This compares with the building energy performance standard (BEPS) for an average residential household of 3.2 persons of 4000 kWh per year. Water heating energy use differences do not affect heating and cooling loads significantly because most of the heat leaves in wastewater through the drain, and with a bathroom exhaust fan most of the moisture never gets to the other parts of the building. The actual internal gains

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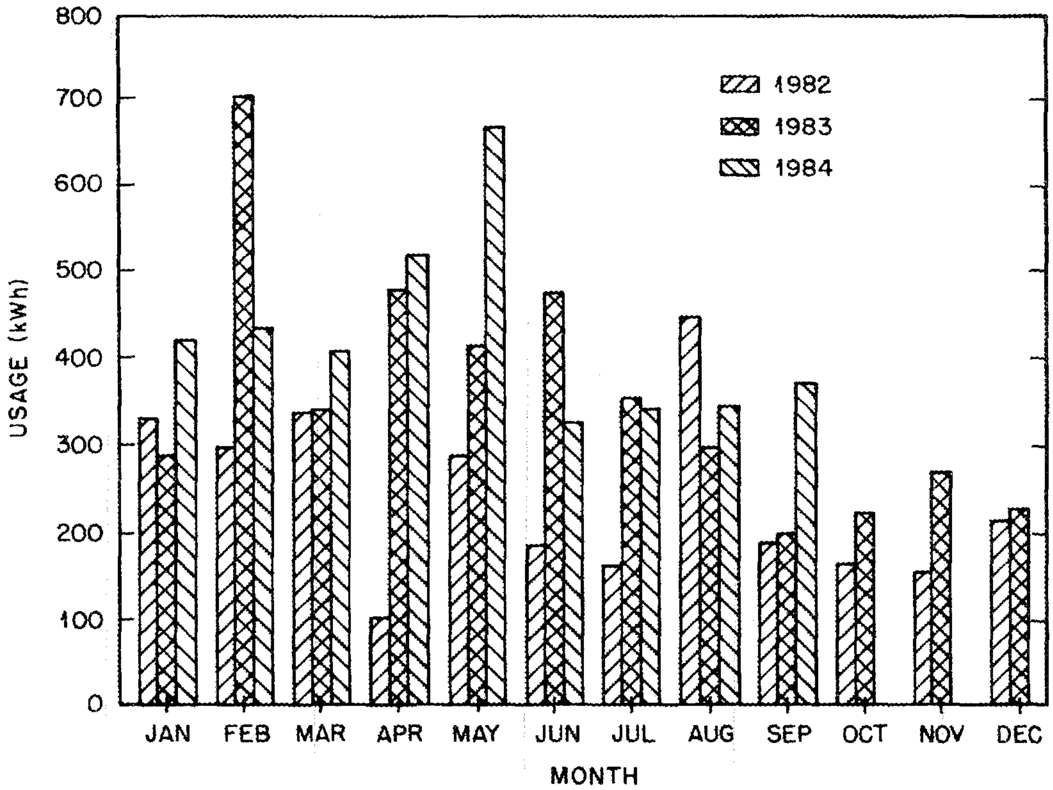

Fig. 7. Water heating monthly kilowatthour usage for 1982, 1983, and 1984.

from water heating amounts to standby losses plus 5% of the remaining hot-water energy use.[5] In this building about 25% of the water heating energy contributes to internal gains.

3.2.5 Kitchen

Figure 8 shows the monthly fluctuation of electric energy use in the kitchen. The kitchen has most of the common appliances found in a residential dwelling; but compared with national averages, they are not as extensively used. The annual kitchen energy use comes to 1370 kWh, compared with BEPS average of 2834 kWh.

3.2.6 Exhaust Fans

Of the two exhaust fans in the building, one in the restrooms and one in the kitchen, only the one in the restrooms is used extensively. The two restroom light switches activate the fan whenever the lights are on. The fan motor uses about 200 W of power and over the years has been found to be left on 50% of the time. The annual electric use to operate the fans comes to about 1300 kWh, or $91.

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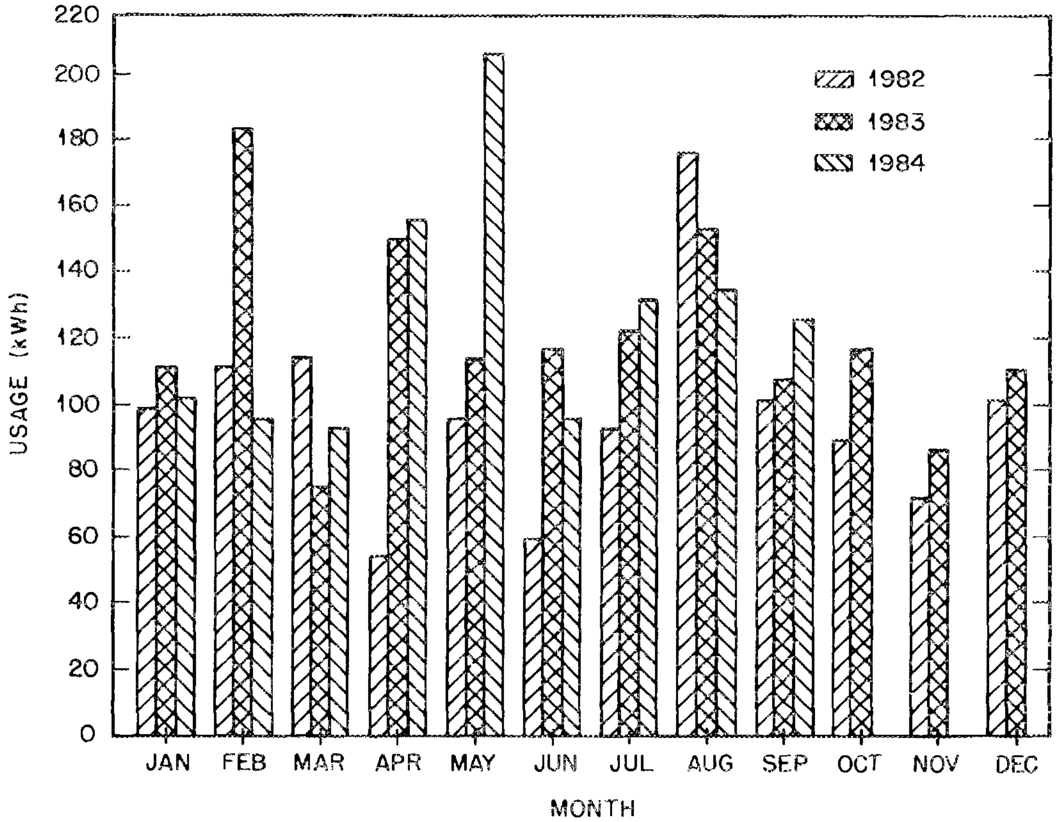

Fig. 8. Kitchen monthly kilowatthour usage for 1982, 1983, and 1984.

3.2.7 Other Energy Use

The rest of the building's electric use consists of the data acquisition system, a fire alarm system, television, and whatever is plugged into the receptacles. Figure 9 shows the relatively constant monthly "other" internal electric use in the building. The annual average "other energy" use totals 4250 kWh. This compares with BEPS assumption of 1400 kWh per year for average size single family residences.

3.3 ENERGY SAVINGS

3.3.1 Using DOE 2.1B Building Simulation Model[3]

Without having two buildings with identical internal usage patterns side by side, estimating energy savings is a bit of an art. A number of different estimating techniques have been used in past reports on this building.[1,2] First, the DOE 2.1B building simulation model was used to model the building using the same weather that occurred during the time measured data were collected. The annual internal electric usage was set as close to the average condition as possible, and the blinds were fixed to operate in a manner that was typical for the building. The model agreement on an annual basis using the DOE 2.1B model

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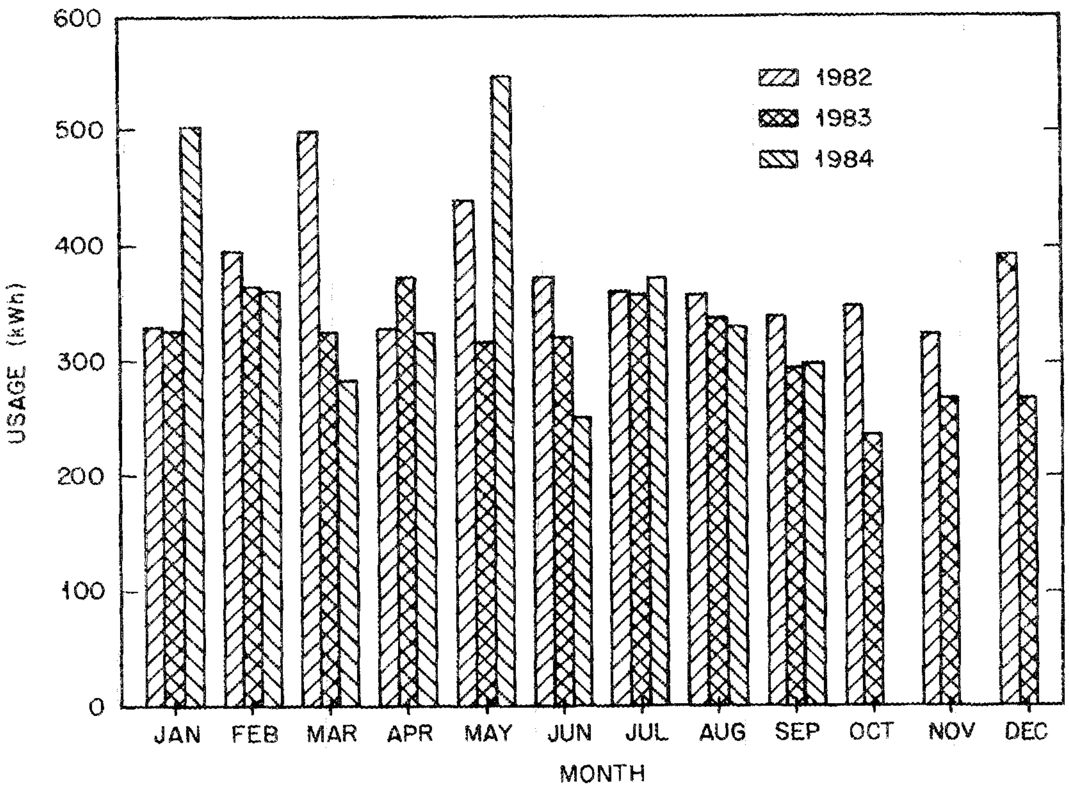

Fig. 9. Other monthly kilowatthour usage for 1982, 1983, and 1984.

was within 17% of the measured data. Using the DOE 2.1B model of the building as the starting point, a second run was made after changing the architectural features to reflect a more conventional above-grade structure. The conventional structure was given a roof with a metric R-value (RSI) of 4.6 $(m^2 \cdot {}^\circ C)/W$ [$R = 26$ $(h \cdot ft^2 \cdot {}^\circ F)/Btu$], walls with an RSI of 2.5 $(m^2 \cdot {}^\circ C)/W$ [$R = 14$ $(h \cdot ft^2 \cdot {}^\circ F)/Btu$], and the same total glass area but redistributed with 50% of the total glass on both the north and south sides. The overhang on the south is 0.6 m (2 ft) instead of 1 m (3.5 ft). In essence removing most of the passive features, earth-covered roof, and bermed walls, the DOE-2 building simulation shows the Joint Institute Dormitory energy savings compared with this above-grade structure to be 30% for heating and 27% for cooling.

Using these energy savings and the measured heat pump usage values of 8100 kWh during the winter season and 5400 kWh during the summer season, the estimated annual energy savings is 5350 kWh.

3.3.2 Using BECA-A Methodology

A second method of estimating energy savings during the heating season only is to calculate a performance parameter on a normalized basis with other buildings and convert the improved performance parameter into an energy-savings figure. A common performance

indicator is provided by the slope of the linear regression line of measured energy input to the space vs some climatic variable reflecting the average inside and outside temperature difference.

Figure 10 shows the actual measured monthly heat pump energy use (in kilowatthours) compared with monthly heating degree days, and Fig. 11 shows measured heat pump energy use (in kilowatthours) compared with monthly cooling degree days. For a meaningful performance parameter, the raw data must be corrected to a standard indoor temperature and a standard internal gain value from internal electric usage and people.

The same cost-effectiveness procedure used to analyze 300 low-energy homes for the Building Energy-Use Compilation Analysis, Part A (BECA-A) is used for this building.[5] The total internal electric load and occupancy pattern of the Joint Institute Dormitory is similar to those typically found in residential single-family houses. Therefore, the building is compared with other low-energy residential buildings.

The BECA-A procedure uses 20°C (68°F) as the standard indoor temperature during the heating season. Internal loads are normalized by defining a correction term,

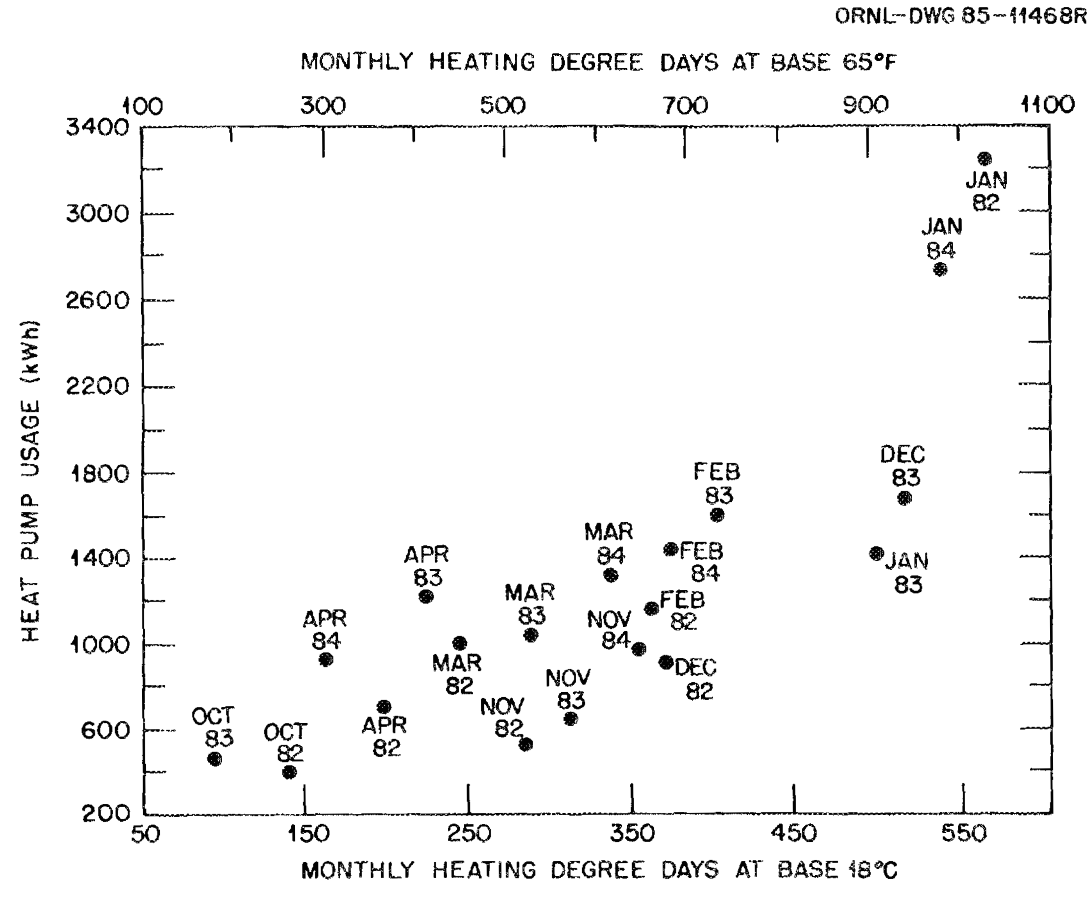

Fig. 10. Monthly heating degree days based on 18°C (65°F) vs heat pump kilowatthour input for 1982, 1983, and 1984.

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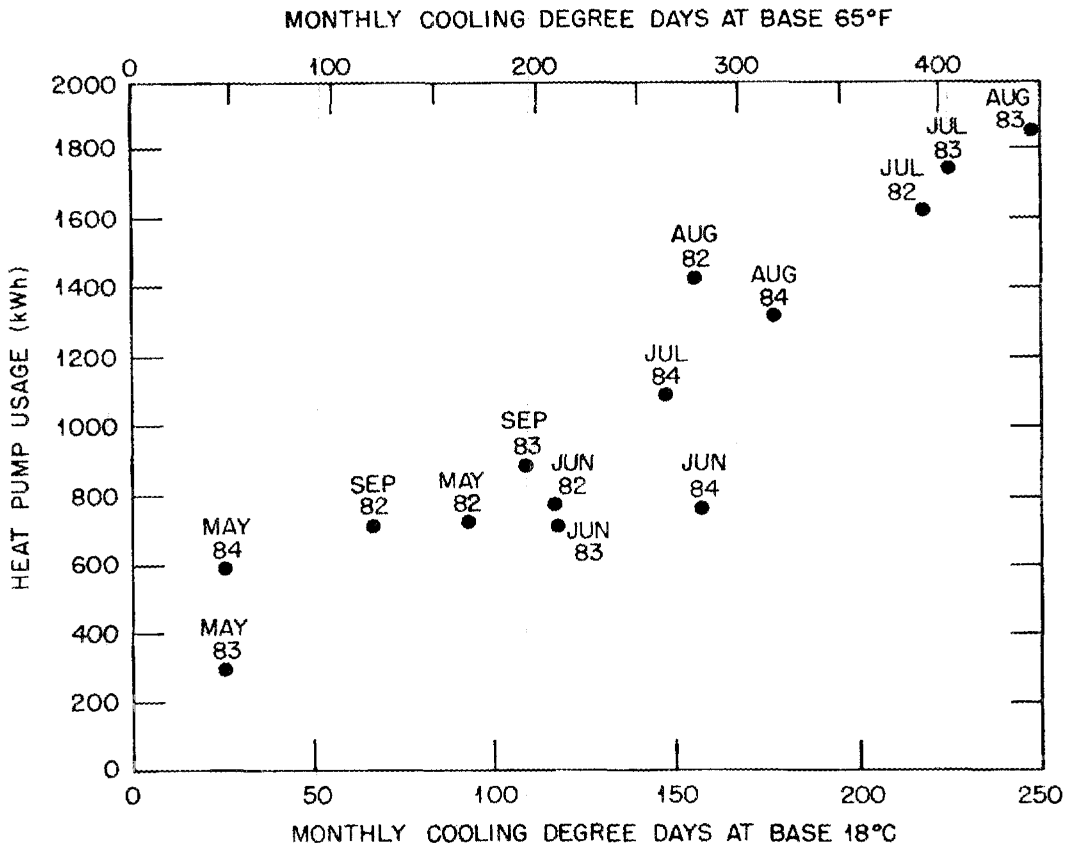

Fig. 11. Monthly cooling degree days based on 18°C (65°F) vs heat pump kilowatthour input for 1982, 1983 and 1984.

$$\Delta I = I_a - I_s ,$$

where I_a represents actual internal gains (in watts).

The term I_s is a floor-area weighted standard internal gains value, which is determined by using the formula[5]

$$I_s = 706 + 3.24\ A_F ,$$

where A_F is heated floor area (in square meters).

The primary performance indicators are the overall effective thermal conductance (watts per degree celcius) of the building and building balance (degree celcius) point. These parameters are determined by plotting the heating system output against outdoor temperature and calculating a linear regression to the data. It reflects the conduction through the envelope, infiltration, and solar gain. The deviation from the standard internal gain value is used to correct the heat input from the heating system,

$$H_c = H_m + \Delta I ,$$

where H_m is measured heat input from the heating system (in watts).

The deviation from the standard indoor average temperature during the heating season is used to correct the average outdoor air temperature.

$$\Delta t = 20°C - T_i ,$$

where T_i is the average measured inside air temperature (in degrees Celcius).

Using the electric energy usage values reported herein, we determined that the average internal gains for the Joint Institute Dormitory for most months were below the standard level. Table 1 shows the monthly values for I_a, I_s, and ΔI. The measured average inside air temperature at the return duct leading to the heat pump during the heating season was 22.6°C; therefore, 2.6°C was used to correct outside air temperature.

Table 1. Internal electric usage normalization

(kilowatthours)

Month	I_a	I_s	ΔI
January	1394	1357	37
February	1194	1269	−75
March	1050	1357	−307
April	1265	1313	−48
May	1765	1357	408
June			
July			
August			
September			
October	1055	1357	−302
November	1097	1313	−216
December	1096	1357	−261

The average normalized UA value for the 300 BECA-A low-energy residential buildings is 114 W/°C (ref. 5). The equivalent overall UA value for the Joint Institute Dormitory is 88 W/°C normalized to the same 100 m^2 of gross floor area. The nine earth-covered buildings in the BECA-A data base average 91 W/°C. The UA value is defined as a thermal performance value representing the whole building, including wall losses and infiltration.

The average balance temperature based on 20°C inside air temperature estimated by linear regression of 12 weeks of winter performance data is 17°C (62°F). The average balance temperature for the nine earth-sheltered houses in the BECA-A data base is reported as 10.2°C. Again continuous use of the circulating fan and extensive use of the exhaust fan are believed to be the cause of the high balance point of this building. The air

change rate in this building is kept at a constant 0.5 air change per hour. The ventilation load in the Joint Institute Dormitory alone contributes 35 to 50% of the total weekly heating requirement in the winter.

Compared with the average energy-efficient homes in the BECA-A data base, the Joint Institute Dormitory has a considerably higher balance point but a lower overall *UA* value. This suggests that the infiltration levels in many of these buldings is far below 0.5 air change per hour or that the buildings have air-to-air heat exchangers. The reader is cautioned not to compare buildings that save energy at the expense of occupant health with other energy-efficient buildings.

3.4 Incremental Cost

The incremental construction cost for an earth-sheltered, passive solar design similar to the Joint Institute Dormitory over an energy-efficient above-ground building is estimated to be $140/m^2 ($13/ft^2) (1984 dollars).[6] This cost differential was obtained from a qualified architect-engineering (AE) firm who generated cost estimates using contractor experience in the Knoxville/Oak Ridge area, from *Means Systems Costs*,[7] and from two sets of detailed blueprints. One set of blueprints were for a 137.5-m^2 (1480-ft^2) residential above-ground house with RSI-5.3 (R-30) ceiling and RSI-3.3 (R-19) walls. This house is equivalent to the Tennessee Valley Authority energy saver home and is believed to be representative of good thermal residential design. Approximately 20% of the homes built in the Oak Ridge area meet or exceed this prototype thermal design. The second set of blueprints were for an underground house designed similar to the Joint Institute Dormitory except that the floor area was only 137 m^2 (1480 ft^2) compared with 372 m^2 (4000 ft^2).

The AE firm provided consistent cost estimates and checked structural considerations to ensure that the bermed walls and support structure for the earth-covered roof were adequate. The structural design considerations were the same as those used in the Joint Institute Dormitory. The cost estimates from this report have been published in several of the popular housing magazines and have produced numerous letters to the editors. However, none of the criticism produced cost information on earth-covered construction techniques that can deliver turnkey units at less than the estimate suggested by ref. 6.

The costs of earth-sheltered construction are also consistent with earth-covered buildings employing barrel construction.[8] The cost for a 670-m^2 (7200-ft^2) gymnasium and auditorium in Belmont, Michigan, was $625/m^2 ($58/ft^2) for earth-sheltered construction.[8] However, only part [370 m^2 (4000 ft^2)] of the building is earth sheltered. This is consistent with the earth-sheltered construction cost estimate used to derive the $140/m^2 ($13/ft^2) differential between earth-sheltered and above-grade construction.

The actual cost for the Joint Institute Dormitory in 1984 dollars was $1356/m^2 ($126/ft^2). In 1983, a second low-energy above-grade office building was built right next to the Joint Institute Dormitory at a cost of $710/m^2 ($66/ft^2). This building has an external insulation system with 10 cm (4 in.) of expanded styrofoam RSI-2.8 (R-16). Monthly electric energy readings show that per unit of floor area, the Joint Institute Dormitory uses about half as much energy to heat as this well-built, above-grade building used for daytime office space only. Other factors accounting for the $645/m^2 ($60/ft^2) incremental cost difference include lower labor rates and considerably less design cost because of the common, above-grade

building construction techniques. However, the large $60/ft^2 actual incremental cost still indicates that the $13/ft^2 assumed incremental cost for earth-sheltered construction is conservatively low.

3.5 Cost Effectiveness

The performance indicator selected for determining cost effectiveness is the cost of conserved energy (CCE), which is defined as

$$\mathrm{CCE} = \frac{I}{E} \times \frac{d}{1 - (1 + d)^{-n}} , \tag{1}$$

where I is incremental investment (in dollars), E is annual energy savings (kilowatthours per year), d is annual discount rate, and n is lifetime of investment (years).

The right-hand term is the capital recovery formula, which converts the incremental investment to an annual payment. The CCE has the dimensions of dollars per kilowatthour. The investment is cost effective if its CCE is less than the price of the energy it displaces. One advantage of the CCE is its independence from future energy prices. It does, however, require assumptions regarding the discount rate and lifetime. The cost effectiveness of this building type can be compared with the BECA-A data base consisting of superinsulated, passive solar, active solar, and other earth-sheltered buildings.

Using the BECA-A assumptions of 3% real discount rate, 30-year life, and DOE-2.1 energy-savings predictions (5350 kWh), the CCE for the estimated incremental cost of earth sheltering with passive solar equals $0.49/kWh. This far exceeds the average national electric rate of $0.07/kWh and suggests that the incremental construction cost cannot be payed back from energy savings alone.

Assuming that the energy savings are accurate, the maximum incremental cost permitted to produce a cost-effective investment would be about $20/m^2 ($1.85/ft^2). If this earth-sheltered building actually used zero energy, the cost savings of another 10,000 kWh could be put toward the incremental investment. Even if this building could be run with zero energy required for providing thermal comfort, the CCE would equal $0.17/kWh, which is more than twice the present average electric rate.

This building can be compared with the BECA-A data base (Table 2) showing *UA* value, balance temperature, and cost of conserved energy. The estimated cost of conserved energy for electric homes (the last column) is based on the energy usage from the National Association of Home Builders 1980 housing stock survey,[9] which indicates an energy savings of 16,070 kWh for the Joint Institute Dormitory during the heating season in the Oak Ridge, Tennessee, climate. Assuming a 50% energy savings during the cooling season saves another 5400 kWh, for a total of 21,470 kWh for the year. The CCE for the comparison equals $0.12/kWh. This is higher than the national average for electricity of $0.07/kWh and would not be considered cost effective according to BECA-A criteria. Table 2 shows the summary of the BECA-A data base and the Joint Institute Dormitory.

The incremental cost of earth-sheltered construction in this building is unlikely to be paid back by energy savings alone. However, a number of factors must be considered in the decision to build underground: aesthetics, site constraints, peak-load savings, tornado

Table 2. BECA-A August 1984 data base compared with Joint Institute Dormitory

Category	Data base[a]		UA^b (W/°C)	Balance temperature (°C)	Conserved energy cost, electric homes (cents/kWh)
	Number	Percent			
Energy saving	319	100	114	12.9	2.8
Superinsulated	196	61	96	15.0	2.1
Passive solar	197	62	104	10.1	2.0
Active solar	26	8	163	13.9	5.7
Earth sheltered	9	3	91	10.2	
Joint Institute Dormitory			88	17.2	12

[a]Sum of the percentages exceeds 100% because many of the buildings incorporate several conservation techniques and are thus counted more than once.

[b]The *UA*-value includes the infiltration term.

protection, an exceptionally quiet inside environment even with close proximity to outside ambient noise such as airports and highways, the ability of an earth-sheltered building to blend well with natural surroundings, the idea itself. The energy-saving concepts employed in this building can be made to work and in a creative, cost-effective manner, given the right set of circumstances. Buildings are not built solely to save energy; they are built for people to use. Earth sheltering can be a viable construction alternative, even if it is not exclusively a cost-effective energy-conservation measure.

4. BUILDING ENERGY-SAVING COMPONENTS

4.1 METHODOLOGY

A computer routine was devised that uses approximately 30 of the hourly thermal performance sensors to conduct a detailed component energy balance calculation with the help of a personal computer spread sheet format. Of the approximately 100 sensor readings, 30 are loaded into a spread sheet. This permits (1) rapid examination of each data element by utilizing graphing and data sorting capabilities and (2) adjustment of the raw data to a useful form. One example of adjusting raw data is that on occasion the kilowatthour submeter in the Joint Institute Dormitory counts an incorrect number of kilowatthours for a given period. The error is almost always by an even fraction because the kilowatthour meters use a small optical sensor/light source, focused to count disk revolutions. It will occasionally pick up three counts per revolution instead of two. The hourly data is corrected by bringing in line the cumulative data to match the daily manual readings.

Typically in a one-week period there will be a half dozen hours during which data are not recorded properly. Using the data base sorting capabilities of the spread sheet programs, these data can be culled and extrapolations from the previous hours used to estimate the true values.

Once the data are corrected, each of the building's major gains and losses is calculated.[1,2] The energy balances provide some confidence that the individual building component performances are accurately measured.

The energy flux of the major energy saving features of interest are measured by heat flow sensors and pairs of thermocouples separated by known resistance of insulation layers within the walls, roof, and floor. Pyranometers are placed inside the south-facing window and on the roof. The extrapolation of these sensor readings to the entire area of opaque surface or window aperture requires some judgment. The position of the reflective insulating blinds was recorded for one blind, and manual recordings in the log book offer some guidance as to how representative this recording of blind position might be.

Because most of the energy consumption in the winter occurs in January, hourly energy balance from a week in this month is presented in Fig. 12. The three lines plotted in Fig. 12 show the total heat gain, total loss, and the residual for each of the hours from January 23 to January 30.

$$R = G - L ,$$

where R is residual, G is sum of all heat gains, and L is sum of all losses. There are very few hours when the residual is zero.

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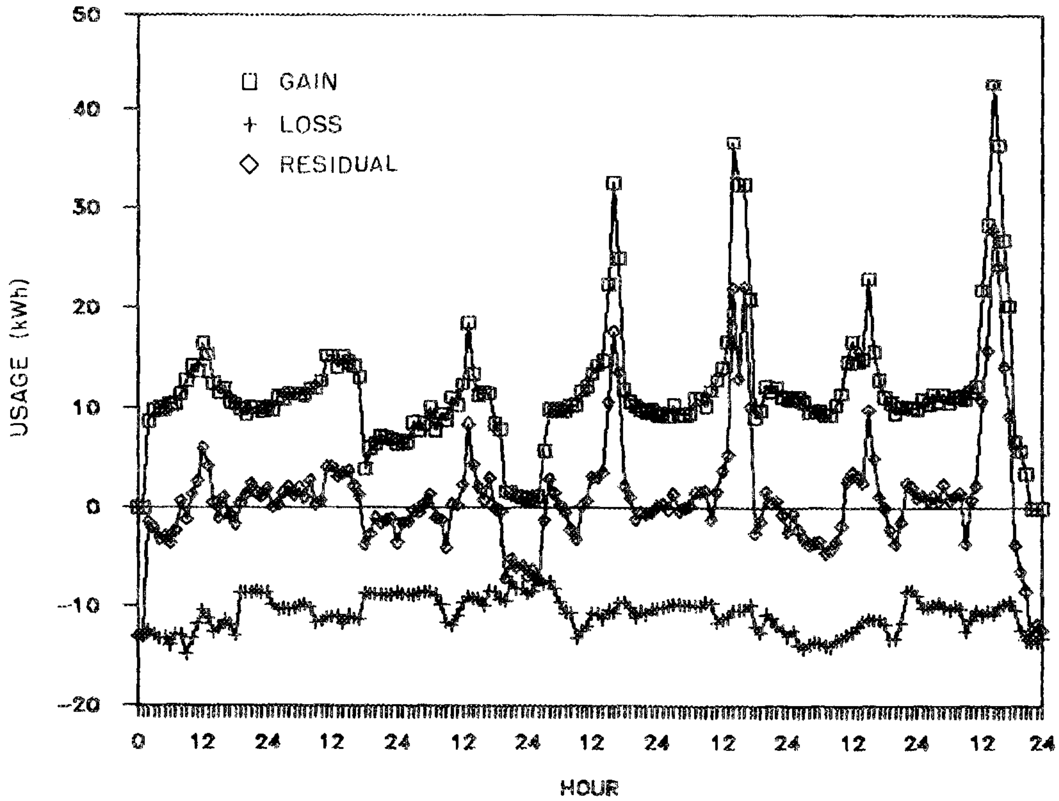

Fig. 12. Hourly whole-building energy balance for week of January 23–30, 1984.

The tall spikes occurring just after 12:00 noon on most days come from solar gain. The internal mass absorption by the interior partition walls is in the energy balance; but the storage effects of the slab floor, external walls, and massive ceiling (onto which most of the direct solar gain is reflected by the reflective insulating blinds) are not included. The average absolute hourly residual is 34% of the measured losses. The maximum residual occurs during peak solar gain periods and for a few hours is almost 300%. The solar gain coming in the window is recorded, but its storage in the interior mass is not measured directly. The heat storage in the inside air is accounted for, but it is very small.

On a daily basis, the energy balance varies from 0 to ±33%. The larger daily residuals tend to occur on sunny days. However, the average residual for the entire week is about 8%. Figure 13 shows the same three values on a daily basis for total heat gain, loss, and residual.

An understanding of the whole week's energy balance can be gleaned from Fig. 14. The largest single gain to the building came from the heat pump (58%), with solar gain contributing only 20% during the relatively cloudy week in late January. The largest single heat loss was due to the 0.5 air change per hour, amounting to about 35%, followed closely by the conduction losses through the south-facing windows, 26%. The reflective insulating blinds were closed on six of the seven nights during this week. The effective window R-value was measured to be about 0.62 $(m^2 \cdot °C)/W$ [3.5 $(h \cdot ft^2 \cdot °F)/Btu$].

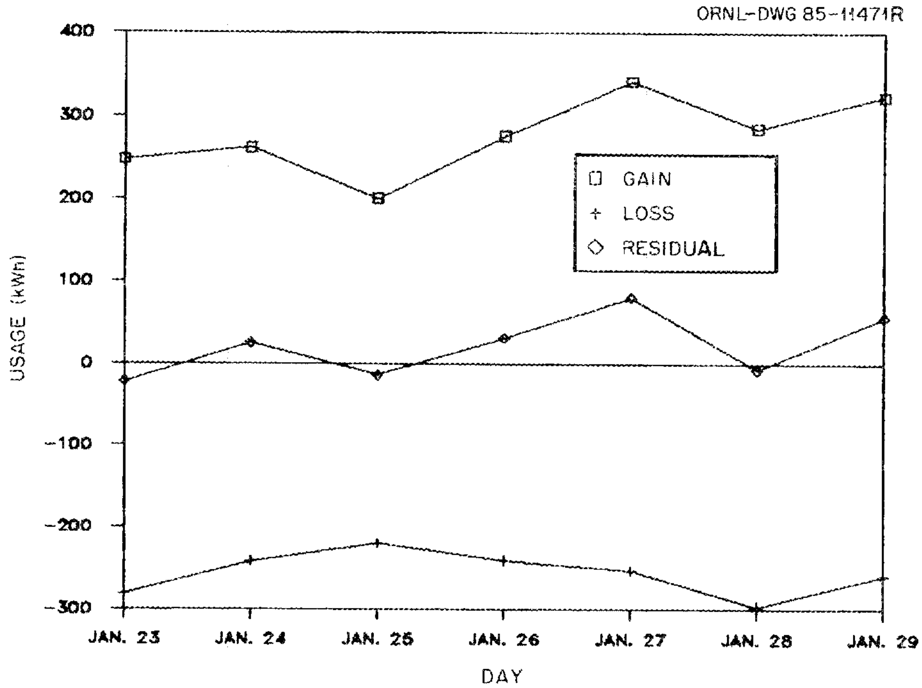

Fig. 13. Daily whole-building energy balance for week of January 23–30, 1984.

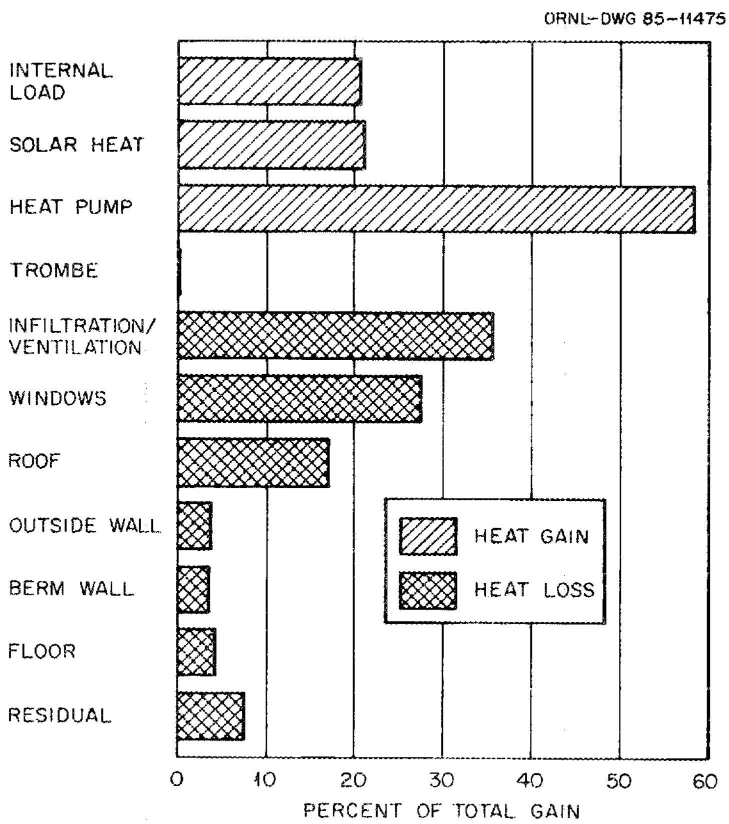

Fig. 14. Percentage breakdown of major heat gains and losses by component for week of January 23 to January 30, 1984.

The sum of the roof losses is around 17% of the total building losses with an effective R-value of about 4.7 $(m^2 \cdot °C)/W$ [27 $(h \cdot ft^2 \cdot °F)/Btu$] during this week. The unaccounted losses or residuals for the week total 8%.

The average outdoor temperature for the week was 2.8°C (37°F) and was more cloudy than average. Most wintertime energy balances show a larger fraction of solar gain, 30–35%. The previous reports on this building show other weekly energy balances.[1,2] This calculational procedure evolved after examining the multiple heat flow measurements in the building and selecting those that appeared to provide the most consistent data. This provides some confidence in the ability to measure the major heat and mass transfer within the building and draw some conclusions about the energy-saving-component contributions from a variety of the unique features of this building.

4.2 EARTH-COVERED ROOF

The heat flux through the roof can be measured using two different sets of sensors. Figure 15 shows the cross section of the roof construction along with the heat flux transducer and thermocouple locations. The heat flux transducer labeled HF2 is a 5- by 5-cm (2- by 2-in.) thermopile positioned in a poured concrete block 10 × 30 × 30 cm (4 × 12 × 12 in.) with approximately the same thermophysical properties as the

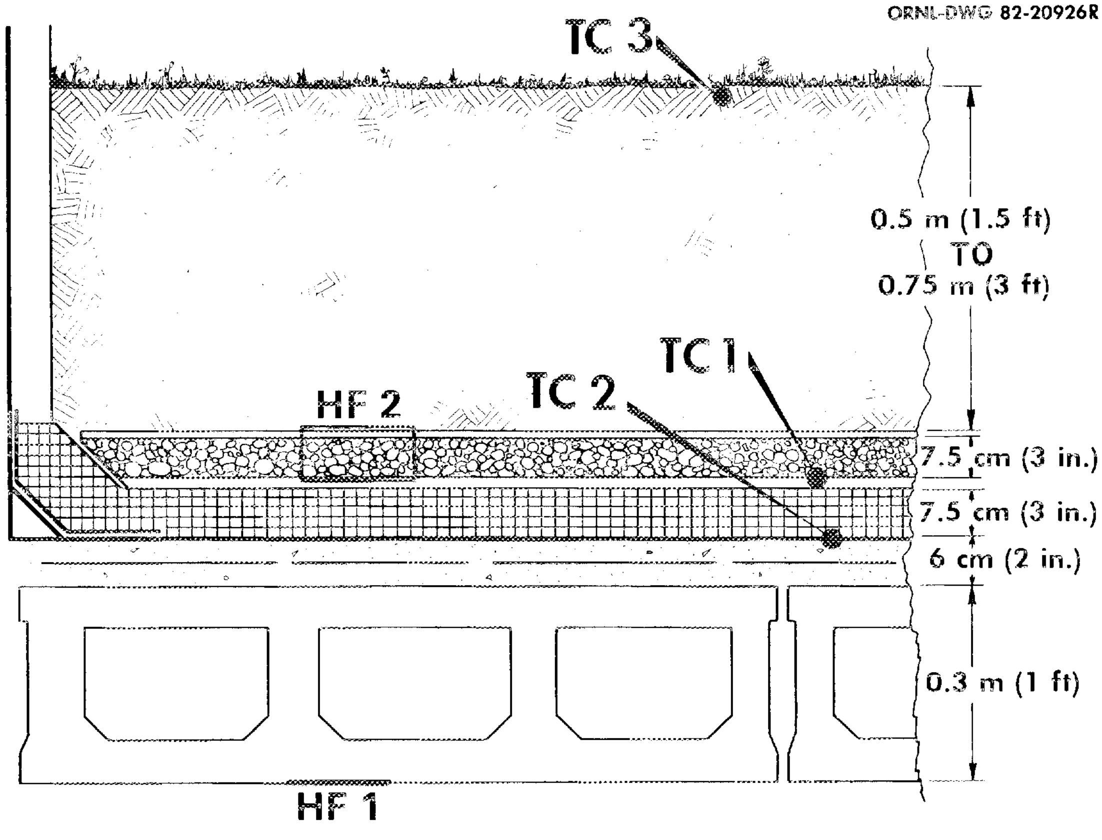

Fig. 15. Cross section of the earth-covered roof section showing thermocouples TC1, TC2, and TC3 and heat flux transducers HF1 and HF2.

surrounding gravel seam. The average measured heat flux values are compared with the estimated heat flux obtained by using average weekly temperature differences (using TC1 and TC2 as shown in Fig. 15) measured across the insulation layer specified by the manufacturer to have an R-value of 2.6 $(m^2 \cdot °C)/W$ [15 $(h \cdot ft^2 \cdot °F)/Btu$]. The steady-state equation is assumed using average weekly temperatures; therefore, the heat flux is estimated using the following equation:

$$Q = \frac{\Delta T}{R} , \tag{2}$$

where Q is the estimated heat flux per unit area of roof, ΔT is TC1 minus TC2 located as shown in Fig. 15, and R is the manufacturer's specified R-value of extruded insulation in the roof.

The two independently derived heat flux values for the roof are compared in Fig. 16 on a weekly basis for January and February of 1983 and 1984. The agreement is reasonably good. Because the average of two sets of thermocouples in the roof gives a better

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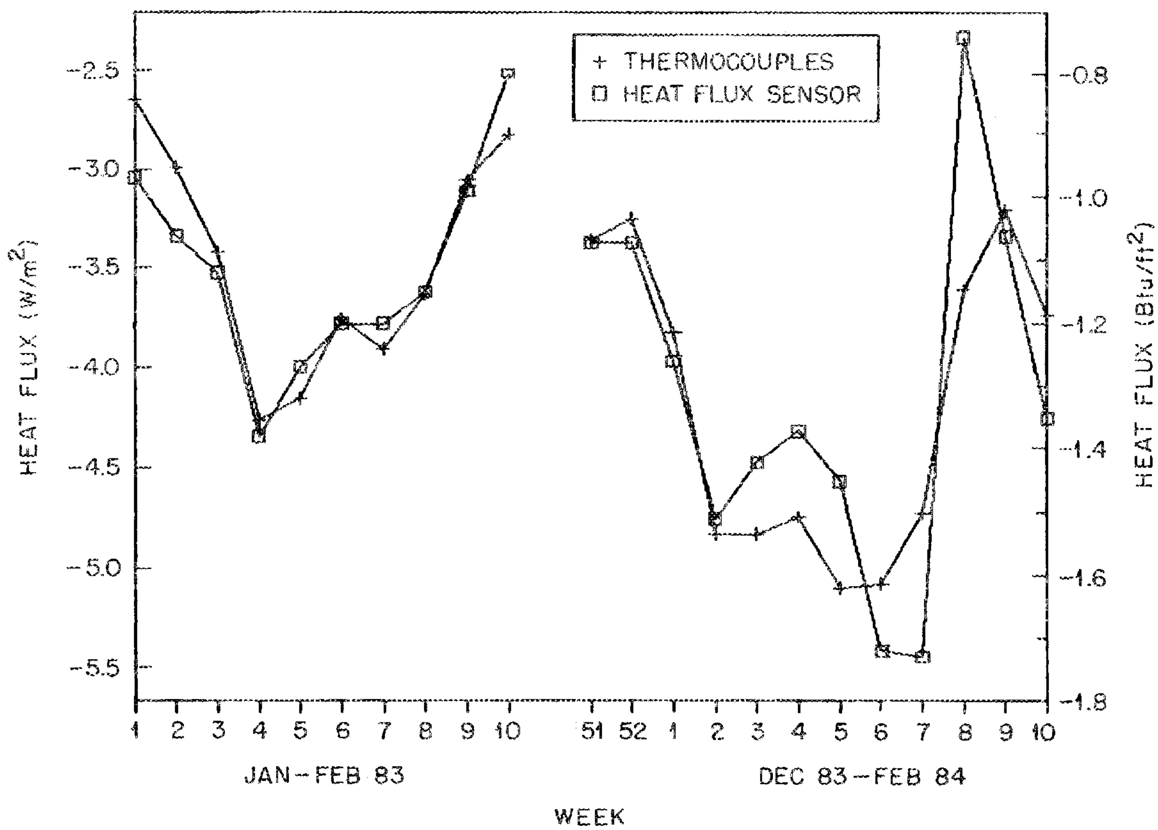

Fig. 16. Comparisons of two different average weekly heat flux measurement methods in the earth-covered roof.

representation of the whole roof, the method of measuring heat flux with the thermocouples is used to estimate the effective R-value of the roof.

The running weekly averages for the coldest two months in 1983 and 1984 are shown in Fig. 17. The average effective R-value for the roof measured during the coldest part of the winter from December through February was about 4.7 $(m^2 \cdot °C)/W$ [27 $(h \cdot ft^2 \cdot °F)/Btu$]. This compares with the steady-state series resistance estimate of 3.4 $(m^2 \cdot °C)/W$ [20 $(h \cdot ft^2 \cdot °F)/Btu$]. The ΔT measured across the entire roof assembly is substituted into Eq. 2 to obtain the effective R-value. The added effective R-value of 1.3 $(m^2 \cdot °C)/W$ [7 $(h \cdot ft^2 \cdot °F)/Btu$] is contributed because of the thermal inertia of the massive roof.

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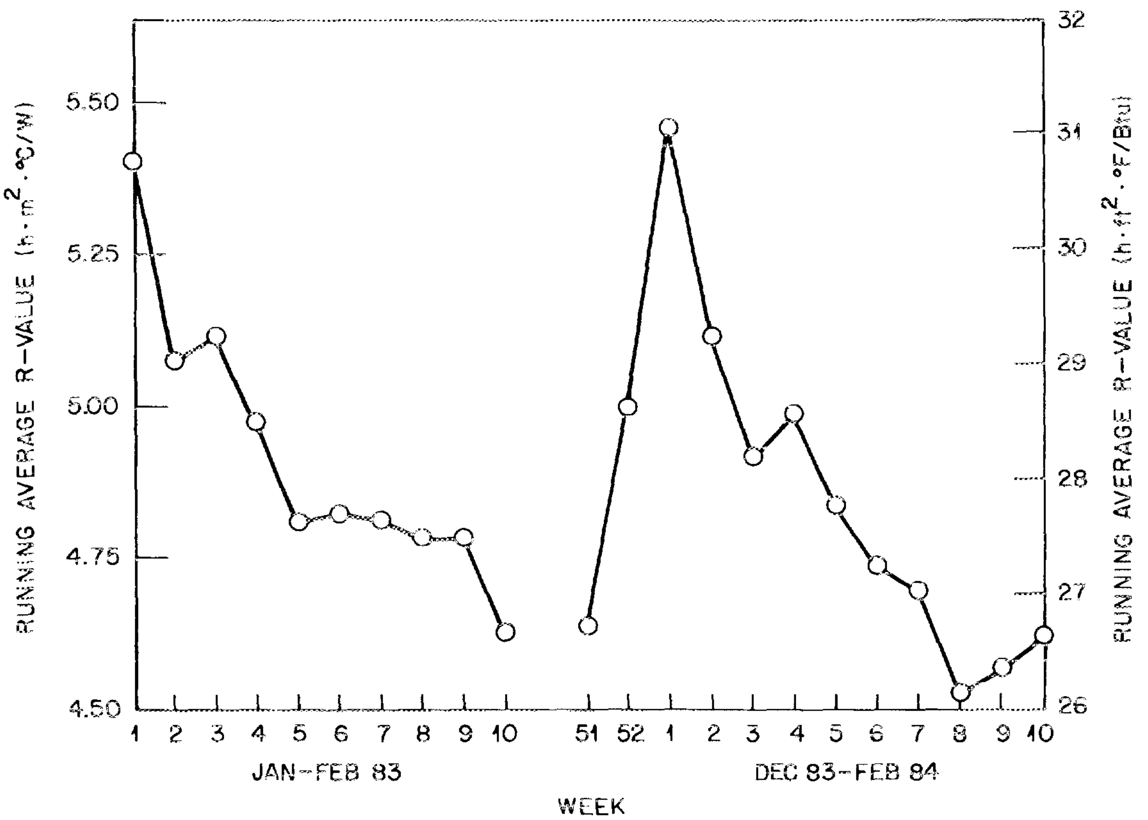

Fig. 17. Running weekly effective R-value of the roof for ten of the coldest weeks from around January 1 to the end of February in 1983 and 1984.

Figure 18 shows a plot of the average weekly outdoor ambient temperature from December 1983 through February 1984. A second plot shown in Fig. 18 shows the effective R-value for the roof for the same measurement period. Sudden temperature drops caused by cold fronts tend to produce a higher effective R-value on the roof. These common short spells of cold are dampened by the thermal inertia of the roof. Weeks 104, 108, and 111 all

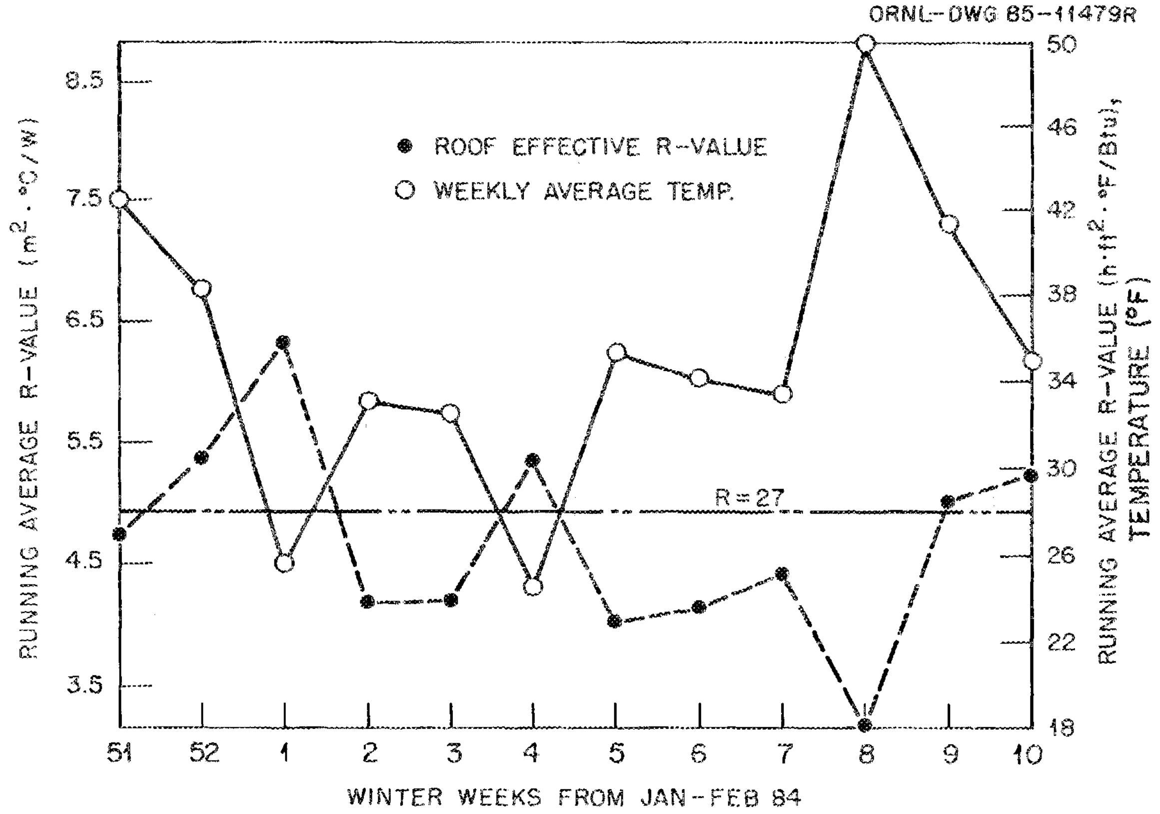

Fig. 18. Plot of average effective R-value and ambient temperature from December 1983 to February 1984.

show this effect. The savings of this phenomena show up not only on the monthly energy bill but also as reduced peak heating demand.

It has been found from this building that placing earth on the roof is far more costly than a conventional roof system, not only because of the higher initial cost, but also because of the leak problems at the roof-parapet wall interface. The theory that in a roof 90% of the cost goes into the flat surfaces and 10% into the interface, yet 90% of the problems occur at the interfaces, held true in this case. Repairing this leak cost considerably more than a conventional roof repair because the dirt had to be removed to get to the membrane. Careful adherence to manufacturer's installation details and error-free application of the membrane could have avoided the leak problem.

The experience gained from this building suggests that at least (1) built-up roofs need more than 2.5-cm (1-in.) slope for every 4.5 m (15 ft) and (2) close attention should be given to roof intersection with parapet walls and other roof protrusions.

4.3 BERMED WALL

4.3.1 Effective R-Value

The heat flux into the bermed north wall is sensed by a heat flow transducer mounted at mid-height on the inside surface of the poured concrete wall. Figure 1 shows the

construction of the bermed wall, which is 25 cm (10 in.) thick with 7.5 cm (3 in.) of extruded polystyrene separating the poured concrete wall from the earth. Detailed multidimensional heat flow modeling indicates that as much as 20% of the heat flowing into the wall actually travels laterally, and furthermore, the slight vertical temperature stratification causes unequal distribution of heat into the wall. Nevertheless, this heat flux transducer is believed to give a fairly good indication of heat flow into and out of the bermed wall over long periods.

Figure 19 shows the hourly measured heat flux for a 2-week period from December 12 to December 26, 1983. The wall is charged up during the late afternoon hours and releases some of the absorbed heat back into the space during late evening hours. The heated space experiences net loss. The shaded area above the zero heat flux value indicates heat coming back into the space. As can be seen by Fig. 19, a much larger portion is absorbed by the wall and is not regained. The net average measured heat loss is used in Eq. 2 to estimate the hourly effective R-value for about 20 weeks in the middle of two heating seasons. The R-value tends to be higher during the early winter because of the stored heat from the summer in the earth berm. The earth temperature in contact with the constructed wall is around 15°C (60°F) in mid-December, and 2 months later the average is around 13°C

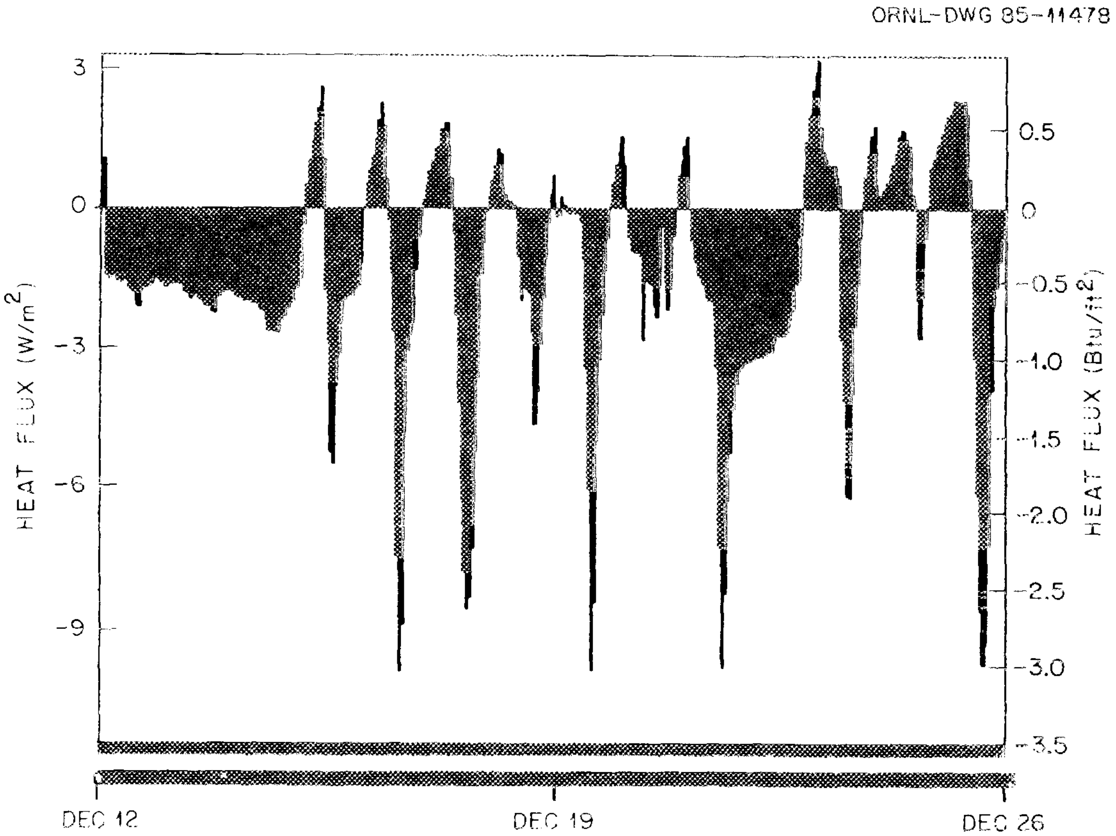

Fig. 19. Hourly measured heat flux in the bermed wall for December 13 through December 26, 1983.

(56°F) in mid-February. This is compared with average air temperatures from −1 to +4°C (30 to 40°F).

The second week in January represents the midpoint of the winter and is used to select the average effective R-value of the bermed wall. The R-value of 10 ($m^2 \cdot °C$)/W [60 ($h \cdot ft^2 \cdot °F$)/Btu] is used to represent the entire heating season for estimating energy savings. The effective R-value is obtained by using the average inside and outside temperatures and the average heat flux measured at mid-height on the inside surface of the bermed wall.

4.3.2 Energy Savings

The method of estimating the energy savings of the bermed wall is to calculate the energy loss with and without the earth. Since this wall faces north, the soil-air temperature is nearly the average air temperature. Equation 3 is used to estimate the heating season energy savings.

$$Q = \frac{U \cdot A \cdot \Delta T \cdot 24}{3412 \cdot \mathrm{COP}} \tag{3}$$

where

Q = heat loss through bermed wall (Btu),
U = heat conduction [Btu/($ft^2 \cdot °F$)],
A = area of bermed wall (1230 ft^2),
ΔT = heating degree day based on 18°C (65°F),
COP = heat pump coefficient of performance.

The use of heating degree days based on 18°C (65°F) is reasonable for estimating heat losses of this building because the balance point is 17°C (63°F). Also, the building has sufficient mass to prevent excessive inside air temperature floating; therefore, the steady-state heat transfer equation works.

The U value used to calculate heat loss without the earth tempering is 0.44 W/($h \cdot m^2 \cdot °C$) [0.077 Btu/($h \cdot ft^2 \cdot °F$)] and for the bermed wall is the measured value 0.1 W/($h \cdot m^2 \cdot °C$) [0.017 Btu/($h \cdot ft^2 \cdot °F$)]. The net energy savings predicted by this method is 1050 kWh in the heating season. The cooling season analysis found that on the average the bermed wall contributed 5.3% of the sensible cooling to the building. Equation 4 is used to approximate the additional energy savings of the bermed wall during the cooling season.

$$Q = C_L \times L_f \times 0.053 \tag{4}$$

where

Q = energy savings of bermed wall,
C_L = annual cooling energy to run heat pump (3915 kWh),
L_f = fraction of latent load.

The net contribution of energy savings of the bermed wall in the cooling season is estimated to be 145 kWh. This leaves an incremental annual electricity savings of about 1200 kWh/year for the bermed wall.

4.3.3 Cost Effectiveness

The incremental cost of a bermed wall is determined by comparing the cost of a block wall insulated with exterior insulation and epoxy-coated finish, which is identical to the exposed outside walls on this building, to the poured-concrete exterior insulated bermed wall. The cost for each wall system is shown in Table 3 (ref. 7). The incremental cost of the bermed wall is estimated to be $23/m^2$ ($2.20/ft^2$). The total incremental cost is $2706. Using Eq. 1 to determine the CCE yields $0.11/kWh. This is higher than the national electricity rate of $0.07/kWh. Therefore, the cost effectiveness for the bermed wall used in this building would not be acceptable. No dollar value for the benefits of the visual screening of the building from the adjacent highway or the sound absorption effect has been assumed.

Table 3. Construction cost of block wall vs bermed wall

	Dollars per m^2	Dollars per ft^2
Block wall		
Eight-in. block wall	70	6.52
Dryvit insulation	46	4.25
Total	116	10.77
Bermed wall		
Plain finish concrete, 25-cm (10-in.) thick, 20,700 kPa (3000 psi)	108	10.06
Extruded polystyrene, 75-cm (3-in.) thick	17	1.60
Waterproof membrane	14	1.31
Total	139	12.97

4.4 REFLECTIVE INSULATING BLINDS

The reflective insulating blinds (RIBs) were installed and partially instrumented for performance monitoring in November 1983. In one location a rheostat was connected to the RIB control mechanism and calibrated to determine the position of the blinds. The optimum position for enhancing daylighting is with the blinds at about 45 to 60° from the plane of the window. The RIBs reflect most of the direct light onto the ceiling and partition walls in this position and permit no direct light to hit desk tops. At night the RIBs are manually closed to determine the actual insulating value of the window system and the degree of enhanced whole-building thermal performance. A heat flux transducer was initially mounted

on the inside surface of one RIB and on the inside window surface. Thermocouples were placed between the window and RIBs and in the inside space.

The measured effective R-value of the windows alone, without the presence of the RIBs at night, is about 0.35 $(m^2 \cdot {}^\circ C)/W$ [2 $(h \cdot ft^2 \cdot {}^\circ F)/Btu$]. With the RIBs closed, the average effective R-value of the window system was measured at 0.56 $(m^2 \cdot {}^\circ C)/W$ [3.2 $(h \cdot ft^2 \cdot {}^\circ F)/Btu$]. This was determined by the average calibrated heat flux transducer taped on the inside of the double-pane window and the measured inside and outside air temperatures. The ASHRAE handbook of fundamentals suggests an effective R-value of about 0.35 $(m^2 \cdot {}^\circ C)/W$ [2 $(h \cdot ft^2 \cdot {}^\circ F)/Btu$] for double-pane glazing, which is consistent with the measured values; therefore, it is assumed that the heat flux sensor could be used along with average temperatures on both sides of the window to indicate the overall R-value of the window when the RIBs are closed at night.[4] The placement of a heat flow sensor in a cavity with the likelihood of convective loops in addition to the potential error of mounting on a highly conductive medium such as glass can result in significant errors.

A second heat flow sensor was also mounted on the inside surface of the one RIB; the sensor placed in this location along with the average temperature on both sides of the RIB indicate an R-value of 0.82 $(m^2 \cdot {}^\circ C)/W$ [4.65 $(h \cdot ft^2 \cdot {}^\circ F)/Btu$] for the RIBs alone. The crack length between each RIB and the border between the RIBs and framing were not sealed tight. Weather stripping built into the design helped, but the quality control during construction left larger openings than should be attainable with better process control. The RIBs installed in this building are first-generation design and were constructed with a very limited research budget.

Although accurate field measurement of the overall window system R-value is difficult, the net thermal performance benefit of the RIBs appears to be offset by two factors. First, the RIBs' presence results in a higher shading factor and therefore reduces the net solar gain into the space. Second, the design concept of storing heat in the massive concrete ceiling may actually cause an increased heat loss through the ceiling. The presence of the RIBs increases reflection of the solar gain 8% during peak solar gain hours when the RIBs are left completely open (as shown on the far right of Fig. 20). The increased reflection of the RIBs was measured by a LiCor pyranometer. When the RIBs are open to the optimum position for daylighting, as shown by the middle two windows in Fig. 20, the window system reflection is 13% greater than when the RIBs are not present during maximum solar gain hours between 10 a.m. and 3 p.m. When the blinds are at the optimum angle, no direct light is permitted to strike the floor or working surfaces of desks. When the RIBs are left closed during sunny winter days, the window reflection increases 40% above the conditions occurring when the RIBs are not present. The initial design of the building called for mechanical flushing of the massive ceiling cavities with return air to enhance the recovery and distribution of stored solar energy. This feature was eliminated from final design because of the added complexity and first-cost considerations. The temperature of the roof where the insulation is fastened to the concrete remains at 16°C (60°F) throughout the winter. With more heat dumped into the ceiling, more heat is conducted through the spandeck, 7.5 cm (3 in.) of extruded polystyrene, and into the earth. The heat flow through the roof was measured for about 10 weeks in January and February of 1983 before the RIBs were installed as well as in January and February of 1984 after their installation. A discussion of how the heat flux is measured can be found in Sect. 4.2. The resulting heat

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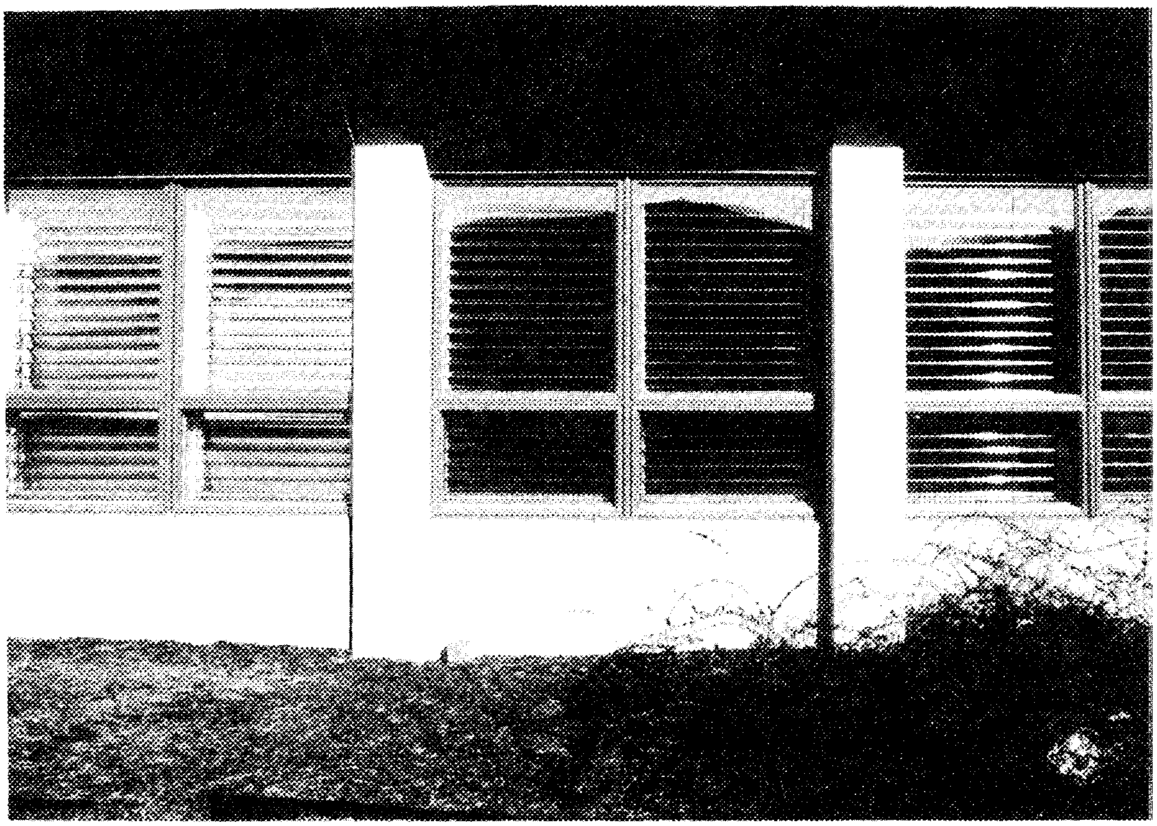

Fig. 20. Picture of RIBs open all the way, optimum position for daylighting, and closed.

flux from these two monitoring periods with and without the RIBs is shown in Fig. 21. The heat flux out of the building is indicated by a negative value. The open circles symbolize average weekly heat flow in January and February without the RIBs. The closed circles symbolize those weeks after the RIBs were installed. On the average, about 25% more heat was lost through the roof after the RIBs were installed.

The overall thermal performance parameter of several months with and without the RIBs can be seen in Fig. 22. The thermal integrity factor [British thermal units per square feet times heating degree days] shows no significant change for December 1983, January 1984, February 1984, or March 1984 (months with the RIBs installed and operated optimally) compared with the same periods in 1982 and 1983 (periods with no RIBs installed). In general, the RIBs greatly improved the comfort and usability of this building and the quality of light was much better. However, the overall thermal performance was not improved. The effective overall thermal conductance and balance point of the building were not significantly changed by the installation and daily operation of the RIBs.

The initial design of the RIBs called for an effective R-value of the window system with the blinds closed of 1.0 $(m^2 \cdot °C)/W$ [6.0 $(h \cdot ft^2 \cdot °F)/Btu$]. If this design specification were

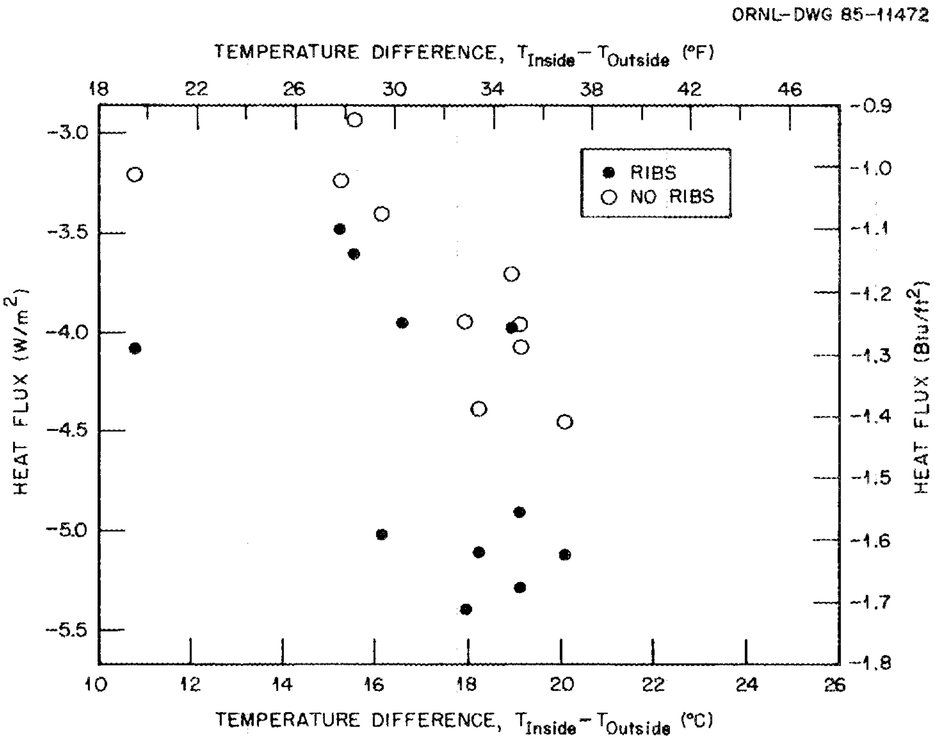

Fig. 21. Temperature average weekly heat loss through the roof as a function of temperature difference across the roof with and without the RIBs.

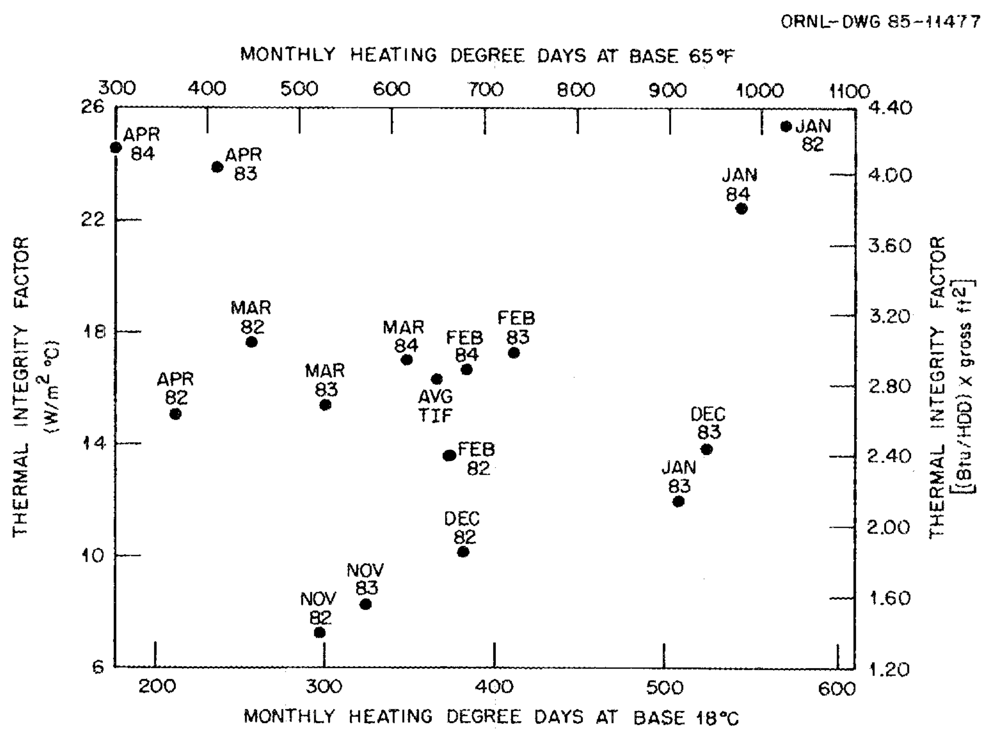

Fig. 22. Calculated monthly thermal integrity factors for several winter months before and after installation of the RIBs.

attained and the blinds were closed every evening during the heating season for 14 h (from 7:00 p.m. to 9:00 a.m.), the expected annual heating load savings in this building is predicted to be around 15%, with a peak heating savings of around 13%. This conclusion is based on DOE 2.1B computer simulation results with and without the nighttime window insulation, using actual 1982 weather data and a best-fit building input file. The 15% annual heating energy savings in this building converts to $37.50 a year at $0.07/kWh and using the 1982 measured seasonal COP of 1.68 for the heat pump. Employing the cost-effectiveness factor defined in Sect. 3.5, the incremental break-even initial cost of the nighttime insulation features alone would have to be about \$19.20/m^2 (\$1.80/ft^2) of glass area.

4.5 THERMAL MASS

The Joint Institute Dormitory was modeled using the DOE 2.1B building simulation code. This version of the code did not have the capacity to account for multiple-dimension heat flows or for the actual thickness of the soil on the roof and in the berm on the north and east walls. The model was calibrated to the building as close as possible despite these deficiencies. Measured average internal electric loads were used along with typical occupancy schedules observed in 1982. To account for the solar shading of the grass, the full roof and bermed walls were shaded with a hypothetical shade screen with zero transmittance; however, the effect of evapotranspiration was not modeled. This seemed to produce larger errors in the summer cooling season than in the winter. The model was able to come within 5% of the measured annual heating energy and 30% of the measured annual cooling energy. Closer examination of hourly data revealed that the model was overpredicting the heat gain of the roof and bermed walls; once this error was accounted for, the cooling energy prediction was much closer to measured values. Comparing hourly measured heat flows into the building from the berm and roof during several typical summer days in late July indicated that the model was overpredicting the heat flow in the roof by an average of 381 W/h (1300 Btu/h) and in the bermed walls by 352 W/h (1200 Btu/h). Figure 23 shows the measured vs predicted heating energy usage for February 1982 and cooling energy usage corrected for the measured effect of soil for August 1982. The heating energy prediction is 3.3% higher than measured, and the cooling energy consumption is 14% higher.

Because the model did not simulate the thermal performance of the soil accurately in the roof or the berm, the soil was removed in the model, and a sensitivity was run to determine the effect of the increased thermal capacitance of all the concrete and masonry components in a building with identical construction as the Joint Institute Dormitory but without the earth covering. A second case was then run with the roof, foundation, exterior walls, and all partition walls modified in the building input file to simulate frame construction with the same conductivity as the massive components in the actual building. Table 4 shows the sensitivity of the added thermal capacity of the massive building compared with the identical building constructed out of insulated frame members.

The first two columns in Table 4 show annual and peak energy usage of the DOE 2.1 massive and frame building simulation models, respectively. The third column shows the percentage energy savings of the massive concrete and masonry components of the building. These energy savings were determined by running two cases, the first (DOE 2.1 massive)

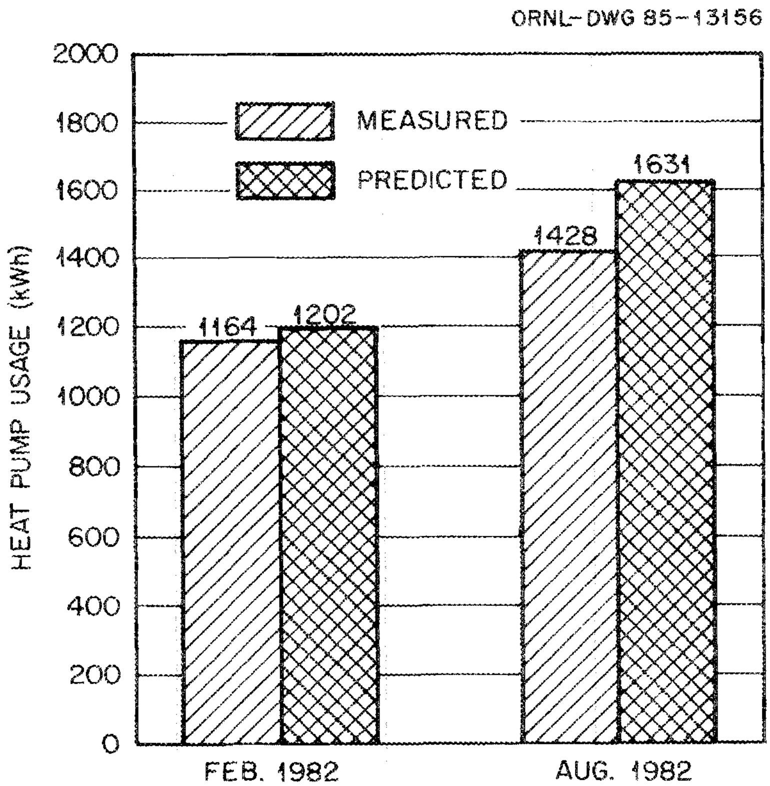

Fig. 23. DOE 2.1 calibration with real building.

Table 4. Whole building performance with massive vs frame construction

	DOE 2.1 (kWh)		Percent savings	JID[a] (kWh)		Energy savings for JID frame and massive (kWh)
	Massive	Frame		Massive	Frame	
			Annual			
Cooling	6486	7187	9.8	3915	4297	382
Heating	4598	5275	12.8	6000	6771	771
Fan power	6174	7771	20.6	3585	4322	737
			Peak			
Cooling	6.017	7.417	18.9	5.3	6.30	1.00
Heating	11.401	13.804	17.4	10	11.74	1.74
Fan power	0.706	0.888	20.5	0.4	0.48	0.08
Sum of heat pump and fan						1889
Annual cost savings at $0.07/kWh = $132						

[a]Joint Institute Dormitory.

was identical to the Joint Institute Dormitory except that the earth on the roof and in the bermed walls was removed. The remaining massive roof, foundation, and exterior walls were all insulated on the outside to the same levels as those found in the Joint Institute Dormitory. The second case (DOE 2.1 frame) was modeled with the same envelope component conductances as the first case; however, the heat capacitance of the roof, exterior walls, foundation, and interior partition walls was reduced from those found in the Joint Institute Dormitory to those representative of insulated frame construction.

The column labeled "JID massive" shows the typical annual energy usage of the Joint Institute Dormitory. This measured energy usage is used to calibrate the DOE 2.1 model energy saving predictions of the thermal mass to the actual building. The column labeled "JID frame" is determined by increasing the Joint Institute Dormitory measured energy usage values by the percentage energy savings predicted in the DOE 2.1 sensitivity comparison. The DOE 2.1 model run with custom weighting factors predicts about a 10% energy savings in the cooling season, 13% in the heating season, and a 21% savings in annual electric usage of the continuous circulating supply fan. This energy savings totals 1889 kWh, or \$132.00 annually, assuming a cost of \$0.07/kWh. Using the cost-effectiveness factor defined in Sect. 3.5, the incremental break-even initial cost of the added thermal mass in the exterior walls, roof, foundation, and interior partition walls would be about \$2600, or \$0.20/ft^2 of surface area exposed to the inside space. The difference in cost between an insulated 8-in. block wall with R-15 exterior rigid insulation and stucco facing and a 2- by 6-in. with 24-in. o.c. wood frame wall with batt insulation is about \$2.20/ft^2 (ref. 7). The cost differential between a wood frame partition wall faced on both sides with 5/8-in. drywall and 4-in. concrete block wall is about \$1.55/ft^2 (ref. 7).

Further sensitivity studies using DOE 2.1 show that the whole building energy savings is a result of contributions from the added mass in all parts of the building located within the insulated envelope. In other words, the energy savings of added thermal mass in the exterior walls depends on mass in the interior partition walls, the roof, and the foundation.

A second observation regarding the prediction of thermal mass energy savings is that there is a relationship between the system sizing and operation. In the DOE 2.1 simulations, the model was permitted to size the system uniformly for all cases. The result was that the model selected a larger size system in the frame building to meet the 18% higher peak heating and cooling loads. This resulted in more energy demand for the fan not only when heating and cooling were required in the building but continuously because the building's occupants preferred continuously circulating air. The larger fan also reduces the efficiency of the HVAC system by adding more heat to the building and increasing cycling losses.

5. CONCLUSIONS

Glass, mass, and earth can be combined to provide a durable, comfortable, and inspiring office-dormitory building. The design objectives were accomplished, operating costs are low, and the owners are very pleased with the product—a commercial building that is both technically sound and artistically unique. To extrapolate the results of the monitoring of this building with other buildings, this study compares the economics of this building in the residential marketplace. This earth-sheltered/passive-solar office-dormitory has internal loads and size very similar to larger residential buildings; therefore, the thermal performance of the whole building is compared with some 300 other energy-efficient residential buildings. However, it is pointed out that this building has mechanical ventilation that ensures about 0.5 air change each hour with no air-to-air heat exchange. The infiltration ventilation load in this building amounts to 35 to 50% of the heating energy. This is considerably higher than many of the very tight buildings in the BECA-A data base used to compare other energy-efficient residential buildings. Ideally, indoor air quality should be normalized before making energy use comparisons. This building was found to perform similar to other low-energy residential buildings around the country; however, when only energy savings are considered, the added cost of this type of construction is not cost effective for single-family residential applications.

The cost and experience of an earth-covered roof and bermed walls in this building strongly suggest that one needs additional reasons for earth covering besides energy savings. Passive solar buildings of this type used in commercial applications most likely will require some type of automated operation system that ensures window management—closed at night and opened by day. So that the space of a direct-gain commercial building can be used intensively, some provision should be made to reflect direct light away from the working space near the south aperture; the inevitable loss of some efficiency should be factored into the energy performance of the building. With the extensive thermal mass of this building, peak load savings are attainable; however, the smaller heating and cooling equipment require precise control to ensure uniform temperatures at all times throughout the year.

6. RECOMMENDATIONS

An earth-covered roof's strongest marketing feature besides its ability to blend well with the natural environment is the potential to minimize the cost of periodic maintenance. Energy savings alone does not justify the added expense of earth covering in the Joint Institute Dormitory. The earth-covered roof system has the potential to attain zero routine maintenance cost. This roof did experience a leak that was caused by poor installation procedures at the roof–parapet wall interface. Once the leak was repaired, the roof performed fine. No leaks have surfaced in the roof since the earth covering was layed down. The key is to make sure there are no leaks before covering the roof with dirt. Typical flooding of the roof which is done before the soil is placed on the roof may not uncover leaks that are above the water level during flood testing but below the water level experienced during a hard rain with the soil in place. The inverted roof insulation position protects the integrity of the waterproof membrane during installation and prevents freeze-thaw damage throughout the life of the building. The minimum measured temperature of the roof just above the insulation was 3.3°C (38°F), and the minimum temperature of the waterproof membrane was 8.9°C (48°F). This was over four winter periods with numerous average daily temperatures below zero and minimum hourly temperatures of −19°F on January 21, 1985. Besides paying more attention to roof interfacing details before earth covering, a second consideration is to slope the roof. The roof on the Joint Institute Dormitory is nearly flat. The earth covered–inverted roof system offers the possibility of making the durability of the roof equal to that of well-built exterior walls by protecting the membrane from freeze-thaw damage and typical diurnal roof surface temperature fluctuations. Material development and systems research that leads to minimal potential for installation error and roof life times of 75–90 years should continue.

The bermed wall in this building is a net contributor to the sensible cooling supply (about 5% of total sensible cooling) in the summer and a very small loser (about 4% of total heat loss) in the winter. Therefore, over an entire year the effect of the bermed wall in this building is neutralized. This observation leads to future improvements in opaque wall thermal performance involving thermal storage so that walls become net suppliers of energy. One frontier in advanced wall systems will be enhanced integration with the building's heating, ventilating, and air-conditioning system.

The cold pocket of earth located at the base of the bermed wall appears to offer additional sensible cooling potential by increased coupling. The bermed wall in the Joint Institute Dormitory was found to transfer about 20% of the absorbed heat vertically down into this cooler earth. Perhaps heat pipes could be buried in foundations to control the use of this heat sink. If the earth contact cooling were controllable, then the fraction of sensible cooling provided by the foundation could be increased substantially.

A second method of controlling heat flow from earth contact systems would be insulation that permits control of the moisture content in such a manner that the conductivity can be

varied by a factor of 10. This concept offers the advantage of high resistance in the heating season and low resistance in the cooling season when sensible cooling is needed.

An effective window-management system for dormitories, hotels, and motels would produce the largest single-envelope energy savings in this building. The windows predominantly facing south permit a net heat gain during the heating season but losses represent almost half of the envelope heat loss total. The transient building occupants cannot ordinarily be depended on to operate manual window management systems. If the system operates optimally, the annual energy savings is small (about 800 kWh) in the Joint Institute Dormitory; however, in larger buildings an automated window management system should be considered.

Moisture condensation or mold production did not occur in this building. The inside exterior wall surfaces never fell below the measured dew point temperature. The earth-contact walls and roof are uniformly insulated with RSI of 2.64 (R-15) extruded polystyrene and the floor with RSI of 0.9 (R-5). The temperatures measured under the floor insulation were very stable year round, averaging 20°C (69°F) with an amplitude of about 0.5°C (1°F). This insulation under the center portion of the slab would be more effective if placed on the roof and the top half of the bermed wall. The net effect would be to reduce envelope heat loss in the winter and increase the sensible cooling effect of the earth contact in the summer.

Wall systems in contact with the earth have a much smaller temperature range in which to operate but a considerably harsher moisture region. The wall in contact with the earth needs to be better protected from moisture penetration and must be structurally stronger. So that bermed walls can be more competitive, the added waterproofing and structural integrity costs need to be reduced. Inexpensive insulating drainage boards are beginning to penetrate the housing market and may attain the cost reductions needed to significantly take advantage of earth contact systems. Extensive field testing of these materials in various geographic locations with different soil types should be conducted to gain builder acceptance.

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